CHARACTERIZATION OF THE CCOS 2000 MEASUREMENT PERIOD

Interim Report (Contract 01-2CCOS)

Prepared for:

The San Joaquin Valleywide Study Agency
and
California Air Resources Board

Prepared by:

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Management District

November 2001

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1.0 INTRODUCTION

To meet the San Joaquin Valley bump-up SIP requirements, meteorological measurements from readily available sources were examined to determine the representative of the candidate CCOS modeling episodes. The two candidate episodes are July 30 to August 2 and September 17 to 22, 2000. This interim report discusses preliminary results from a variety of description and statistical analyses.

Synoptic scale weather charts were obtained for the period June 1 through October 2 that encompassed the CCOS field program. The large-scale meteorological features that are relevant to Central California air quality leading up to and during ozone episodal periods were determined and are described in Section 2.

The sub-synoptic meteorological features for the two candidate episodes are described in Section 3 with an emphasis on the San Joaquin features relevant to air quality, specifically the nocturnal jet and Fresno eddy characteristics. Radar wind profiler measurements from several sites in the San Joaquin and Sacramento Valleys were examined. It should be noted that the measurements used were downloaded from the internet and, to the best of our knowledge, have not been validated by NOAA or the CRPAQS Data Manager.

The results of statistical analyses are discussed in Section 4. A comprehensive suite of meteorological parameters were subjected to cluster and principal component analysis for the 11 year period from 1990 (AUSPEX/SJVAQS) to 2000 (CCOS). The meteorological scenarios (clusters) observed during CCOS are compared with the extended period of record. Other analyses included computing the winds aloft direction and speed frequency distributions at 500 mb (~5.9 km) for the most recent 15-year record of National Weather Service rawinsondes taken at both Oakland and California. The annual frequency distributions were examined. A third type of analysis to determine the principal harmonics of major synoptic features to look for distinguishing characteristics was planned. However, this analysis was not completed in time for inclusion into this report.

This analysis was conducted using only readily available data much of it not quality checked. With the exception of five NOAA radar wind profilers, the discussions contained herein do not include analysis of the comprehensive set of special measurements made during CCOS. The information contained herein is intended to provide "fast-track" guidance for modeling, and only a beginning to the understanding of the meteorology and air quality encountered during CCOS.

2.0 SYNOPTIC WEATHER SUMMARY - CCOS2000 PROJECT

The relationship between the dispersion of ozone and ozone precursors in California and large-scale synoptic weather patterns is well known. During the summer ozone season, the extension of the eastern Pacific high over the western US effectively blocks the influx of cyclonic weather systems into California from the Gulf of Alaska, and allows the entrenchment of large static air masses which are typically warm, stable, and poorly mixed. The strength and persistence of the resultant boundary layer mixing and transport patterns affects the magnitude and duration of ozone events in Central California. High pressure ridges and low pressure troughs in the mid to upper atmosphere are particularly efficient indicators of ozone formation conditions. With this in mind, a summary of synoptic meteorological patterns at the 500 mb constant pressure level and, their relationship with ozone occurrence during the CCOS project, is presented in this section.

Figure 2-1 shows plots of the time-series of maximum hourly-averaged ozone concentrations in three areas of the San Joaquin Valley (SJV) during the Central California Ozone Study (CCOS) of 2000. Daily maximums were determined independently for the northern, central, and southern regions of the SJV. The study period was from June 1 to October 2, 2000. The CCOS 2000 study period was characterized by low ozone readings but moderately high ozone was experienced in the southern SJV during September. As can be seen from the figure there are frequent peaks and valleys indicating short-lived periods of clean and polluted air throughout the summer. In general, the central and southern regions (Fresno and Bakersfield areas) experienced the highest readings, while the northern area (Stockton and north) experienced the lower maximums.

A summary of the periods of peak and minimum ozone occurrences. are presented in **Table 2-1.** The Intensive Operating Periods (IOP) dates are also shown in the table**.** Note that the project IOP did capture the periods of highest ozone maximums as designed for.

Table 2-1. Periods of minimum and peak ozone levels during CCOS 2000 with IOP dates

Minimal Ozone Occurrence	Peak Ozone Occurrence	IOP Dates
June 8 through 10	June 3, 15, 22, and 27	June 14 & 15
July 3 through 6	July 11, 22 through 25	July 23 & 24
Aug. 10, 28, and 17	Aug. 1 and 3	July 30 & 31, Aug. 1 & 2
Sept. 14 through 17	Aug. 13 through 17	Aug. 14
Sept. 28	Aug. 24 through 27	Sept. 14
	Sept. 10 through 14	Sept. 17-21
	Sept. 17 and 26	Sept. 23 & 24
	Sept. 29 through Oct. 2	Sept. 30 through Oct. 2

Two synoptic scale meteorological parameters, which historically have correlated well with ozone formation and fate in California, are the height of the 500 mb surface and the temperature at the 850 mb level. The time history of 500 mb heights a fixed location is a general indicator of the behavior of the 500 mb surface indicating pressure ridges and troughs. The 850 mb temperature is a measure of large scale subsidence which produces stable layers in the atmosphere and limits vertical dispersion of ozone and precursors. **Figure 2-2** shows plots of the afternoon 500 mb height and the 850 mb temperatures measured daily at the Oakland (OAK) NWS station during the duration of the CCOS program. The figure illustrates a strong correlation between the 500 mb height and the 850 mb temperature height. In addition, when compared to Figure 2-1, a strong correlation also exists between the maximum ozone concentrations and the 850 mb temperature and 500 mb height.

2.1 Summary of the 500 mb Height Surface

Figures 2-3 through 2-15 present the afternoon 500 mb synoptic weather patterns for selected days during the four-month CCOS 2000 field program. These daily afternoon 500 mb constant pressure charts were extracted from the NOAA, National Weather Service (NWS) Storm Prediction Center (SPC) archives, and were modified for presentation by T&B Systems meteorologists. A narrative summary of the synoptic meteorological patterns and ozone dispersion based on the 500 mb charts and upper air 850 mb temperatures and 500 mb heights measured daily at Oakland (OAK) is given below.

During the first four days of June 2000, the western United States, and the project area, was dominated by a high pressure area centered near the Four Corners area in the southwest US. At the same time, a moderately deep low pressure area was moving out of the Gulf of Alaska into the Pacific Northwest. The highest 500 mb height recorded at OAK during this period occurred on June 3rd (5,880 m) and was associated with a peak 850 mb temperature of 18^{o}C. Also on that day, the highest ozone readings during the first 10 days of June occurred, with concentrations higher in the southern SJV than in the northern portion. The westward extension of the high pressure area was more dominant in the southern half of California, while the northern part of the state became more and more under the influence of the low moving out of the Gulf of Alaska. In general, the ozone event in the first part of June was only moderate and was more confined to the southern part of the project area. **Figure 2-3** shows the 500 mb configuration for the first 10 days of June. By late June 4th, the low in the Gulf of Alaska, and trough extending southward from it, began to influence the synoptic weather pattern in the project area as it eroded and dug into the high pressure that was still located near the Four Corners area. The Four Corners high maintained its central peak height of 5,910 m through the June 7th, but the center did begin to drift eastward as the trough continued to dig into the West Coast. By June 7th, a distinct was along the coast and flow aloft was from the southwest promoting an influx of cooler air in the lower levels. By June 8th, the OAK 500 mb height had dropped to 5,650 m and the 850 mb temperature had decreased to 7^{o}C. At the same time, ozone readings throughout the project area had dropped to their lowest levels for the first ten days of the month.

On June 9th, the 500 mb trough passed over the West Coast and began to migrate into the interior. This signaled the onset of higher pressure migrating from the eastern Pacific towards the project area behind a low pressure trough. **Figure 2- 4** shows the 500 mb synoptic pattern as it progressed during the period from June 9 through 15. The first IOP occurred June 14-15. The peak central pressure of the slowly advancing eastern Pacific ridge was around 6,000 m during this period. The center of the ridge was still located west of Oakland on the afternoon of the 14th.

The OAK 500 mb height had increased from a low of 5,650 m on the June 8 to a maximum of 6,000 m on June 14. During that same period, the OAK 850 mb temperature increased from 7°C on the June 8 to a high of 27°C on the June 14. As the ridge progressed towards the east-southeast, flow aloft remained from the north throughout the period. This slowly encouraged the onset of offshore flow across the project area during that time. Ozone concentrations increased steadily as the ridge approached with peak ozone values in excess of the Federal and State Standards occurring throughout the valley during the IOP period.

The period from June 16 through 29 was characterized by generally high pressure and elevated ozone levels, but the strength of the ridge did not develop to the point as to maintain a significant long-run ozone episode. **Figure 2-5** shows the configuration of the 500 mb synoptic pattern during that period. The eastern Pacific high pressure area which, had produced the IOP conditions of the 14th and 15th regressed to the north and west during the next several days as a strong long-wave low pressure trough, centered over the Central Plains, dug into the Western Plains and Rocky Mountains. As a result, the 500 mb heights fell over the West and 850 mb temperatures decreased from the highs of June 14 and 15. Finally by the June 18, a short-wave trough had developed in the 500 mb flow across the West and moved across Northern California into Nevada by late in the day. By June 19, the Eastern Pacific ridge began to slowly migrate towards the east again and 500 mb heights at Oakland began to rise as a result. By June 21, the ridge had reestablished its influence on the project area with the OAK 500 mb height rising to 5,870 m and the 850 mb temperature up to 23°C. During the period, ozone concentrations in the southern part of the project area had increased to levels similar to those experienced during the IOP of the 14th and 15th. This situation, however, was short-lived as the ridge quickly weakened again over California and flattened into a broad, rather flat diffuse area of high pressure across the Southwest and the southern half of California by June 22. The 500 mb heights decreased during this period, as well as the 850 mb temperature, however, not to the degree that would be indicative of strong troughing. The lowest OAK 850 mb temperature was 20°C (on June 6) and the 500 mb height at OAK did not drop below 5,860 m. By June 24th, the Eastern Pacific ridge once again begun to reassert itself from the northwest and 500 mb heights began to rise once again. By June 27, the center of the ridge was located just offshore and to the west of Oakland and OAK 500 mb heights had risen to near 5,900 m. During the 3-day period from June 27 through 30, the OAK 850 mb temperature remained around 24°C and the OAK 500 mb height stayed near 5,900 m as ozone concentrations once again increased throughout the project area.

Late on June 29, the high pressure ridge that was associated with elevated ozone concentrations in the project area during the previous two days had begun to weaken as a troughing situation began to take hold. The first sign of this was the passage of a weak short-wave trough in Northern California that brought some cooler air aloft and stronger onshore flow to the Bay Area and the Sacramento Valley. This feature acted as the precursor (door-opener) to the much stronger troughing that was to come. **Figure 2-6** shows the 500 mb height pattern during the period from June 29 through July 9. This was the second period of extended troughing that occurred during the four-month CCOS project. With this trough, the OAK 500 mb heights dropped from 5,820 m to 5,740 m, and the OAK 850 mb temperatures dropped to as low as 8°C by July 5. Ozone concentrations throughout the project area reached some of their lowest levels of the summer during this 10-day period.

The troughing situation finally ended by July 11 as a large, broad high-pressure area, which had been dominating the southern half of the U.S., began to regress slowly westward. In response, the cool trough that had been situated along the West Coast for many days likewise moved westward. By July 12, the trough was located well off the Northern California and Oregon coasts. At that time, the center of the large high pressure ridge had moved into western Texas and extended through the northern Rockies well up into Canada. This strong ridge, which had a central peak height of 5,960 m, continued to retrograde westward during the July 13 and 14. By July 15, the center was located near the Grand Canyon and the elevated 500 mb heights had extended over California and west into the eastern Pacific. As the 500 mb heights increased (5,900 m at OAK on the July 15), the OAK 850 mb temperature likewise increased to near 20^{o}C on July 15. Ozone concentrations, particularly in the southern half of the SJV, also increased during that period with peak values exceeding the State Standard every day from July 11 through July 15. However, the strong ridge did not quite regress far enough west to induce an IOP-type ozone episode. **Figure 2-7** presents the 500 mb analyses for this period.

On July 16, the high pressure ridge began to progress eastward again, to near the Texas Panhandle, and a short-wave trough developed behind it along the Pacific Northwest Coast. This feature slipped into Northern California by the afternoon of the July 16. The troughing, however, was relatively short-lived and dissipated over the project area by July 19, as flat ridging began to once again build from the east towards the Southwest U.S., and the southern half of California. **Figure 2-8** shows the evolution of this 500 mb pattern during the period from July 15 to the IOP event, which took place on July 23 and 24 . By July 20, the ridge had elongated and tilted from the southern plains all the way across the Southwest U.S., and the southern half of California. The 500 mb heights continued to rise in that area during the next several days as a strong closed omega ridge developed with the center once again near the Four Corners area. The OAK 500 mb height was up to 5,900 m on July 20, and the 850 mb temperature rose to almost 23^{o}C during that period. A short-wave troughing event in the northern part of California on the July 22 caused the 850 mb temperature to drop slightly on that day, but then the ridge continued to build more strongly again on the 23rd and 24th, allowing the two-day IOP exercise. Figure 8 shows the progression of the synoptic pattern leading up to the two day IOP.

By July 25, the ridge had weakened slightly and dropped southeastward into eastern New Mexico and a trough developed along the West Coast from Point Conception to British Columbia. This resulted in the lowering of 500 mb heights and 850 mb temperatures somewhat during July 25 and 26. However, on the 27th, the high pressure ridge once again regressed towards the west and strengthened somewhat to become centered once again in the Four Corners area. With this regression of the ridge, the 850 mb temperature and 500 mb heights at OAK once again rose during that period and continued to rise through July 30 , and the period of the next IOP. During the IOP of July 30 through August 2, the ridge remained strong and continued to slowly regress towards the west until it was centered near Reno, Nevada by July 31. The OAK 850 mb temperature during the IOP reached as high as 27^{o}C and the 500 mb height topped at 5,970 m. **Figure 2-9** depicts this sequence of events.

Elevated ozone concentrations persisted in the project area for several days after the IOP, which ended on August 2. Concentrations exceeding the state and federal standards occurred on the 3rd and some were still detected as late as August 5 in the central and southern part of the SJV. As late as the 5th, the high pressure ridge and associated high 500 mb heights continued. By August 6, the ridge was weakening. During the period from August 7 through 9, a low pressure system developed in the eastern Pacific off the California coast resulting in a notable decline in the OAK 500 mb height and 850 mb temperature. On August 10, the closed low opened up into a sharp trough which extended from the Fresno area northward along the valley and on up into the Pacific Northwest and British Columbia. This sharp trough progressed eastward during the 10th filling as it moved into the Great basin on August 11. After the passage of that trough, the Western U.S. south of 45^{o} N lat. became dominated by a broad, rather flat, area of high pressure that extended from the Pacific to East Coast. At the same time, a low pressure area in the Gulf of Alaska approached the British Columbia coast, but the effect of that feature was not felt south of the California-Oregon border. With the onset of the flat ridging, OAK 500 mb heights did rise again up to 5,890 m and the OAK 850 mb temperatures increased to near 22 C. Ozone concentrations in the SJV responded to these rises with values exceeding both the State and Federal Standards, occurring particularly in the central area from August 12 through August 17. This included the short IOP day on August 14. The highest OAK 850 mb temperature during this period occurred two days after the IOP concluded, topping out at 24^{o}C, while the OAK 500 mb height increased to 5,920 m. Troughing associated with a closed low in the Gulf of Alaska finally dug into the western edge of the broad ridge by August 17, resulting in the lowering once again of the OAK 500 mb height from 5,920 m to 5,880 m on the 17th and a decrease of 4^{o}C at the 850 mb level. On the August 17, the SJV also experienced a reduction in peak ozone levels to below the State and Federal Standards, except for a few readings around 115 ppb in the southern portion. **Figures 2-10 and 2-11** show the sequence of the 500 mb pattern from August 4 through 18.

Weak troughing associated with the 500 mb low moving out of the Gulf of Alaska and across British Columbia affected the West Coast as far south as the northern SJV during August 18 through 21, culminating in the formation of a weak, closed low off the Northern California Coast on the 21st. During this period, 500 mb heights over the project area remained moderately high and 850 mb temperatures dropped only to a low as 16^{o}C, but these parameters did not indicate a strong influence from the troughing. In fact, ozone levels still remained relatively high in the SJV, with some readings in the southern portion continuing to exceed the State Standard. During the period from August 24 through 27, the 500 mb ridge, which was centered in Texas, elongated and tilted back westward resulting in a slight increase in 500 mb heights at Oakland again and a rebound of the 850 mb temperature. The OAK 500 mb height reached 5,900 m on the 25th, while the OAK 850 mb temperature exceeded 20^{o}C. The southern and central SJV ozone values were most indicative of this increase in the ridge’s influence. Once again State and Federal clean air standards were exceeded in those areas but the northern part of the Valley remained below the standards. **Figure 12** shows the 500 mb patterns for the period from August 20 through 28.

By August 28, the broad, flat high pressure ridge progressed into the southeastern U.S. leaving lower pressure in the western U.S. and backflow monsoonal conditions in the southwestern U.S. This eventually led to broad scale troughing along the Pacific Coast by August 29, a pattern that was to persist to September 7. **Figure 2-13** shows the development and persistence of the troughing feature during that period. The OAK 500 mb heights dropped from 5,860 m on August 28 to as low as 5,700 m on September 4. Likewise, the OAK 850 mb temperature decreased from near 20^{o}C on the August 28 to 15^{o}C on August 30, and reached a low of 6^{o}C on

September 3. No ozone concentrations exceeding Federal or State Standards were measured during the period. Indeed, this was the cleanest period of the entire summer.

The deep West Coast troughing pattern of early September slowly migrated eastward on September 8 and 9. By September 10, a high pressure ridge was once again building from the eastern Pacific into the southern half of the United States. **Figure 2-14** shows the evolution of the 500 mb ridge that dominated the synoptic weather pattern in the project area during the period through the mid-September IOP and from the17th through the 21st. During the initial building of the ridge that began on the 7th, ozone values in the central and southern portions of the SJV exceeded the State and Federal Standards every day through September 11. During that time, the 500 mb height at OAK increased to as high as 5,890 m on the 11th and the OAK 850 mb temperature increased from around 18^{o}C to 22^{o}C on the 13th. The northern portion of the SJV did not experience ozone concentrations above 100 ppb during that period as the main influence of the ridge was in the southern half of California. On September 14, the general ridging was curtailed for several days as a trough of low pressure off the Pacific Coast dug southwestward from a low centered off Washington and Oregon. During the three-day period from the 14th through the 16th, the OAK 500 mb heights dropped a bit to around 5,850 m and the 850 mb temperature decreased by 10^{o}C on the 14th down to a low near 12^{o}C before increasing again up to 18^{o}C by the afternoon of September 16. During this three-day period, only the south portion of the SJV experienced a State exceedance. By September 18, the trough had filled and moved eastward opening the door for another high pressure ridge to fill into the West Coast and join with the remnants of a persistent Four Corners high. Once the ridging recovered throughout the west, the OAK 500 mb heights increased quickly again to as high as 5,970 m on the 18th, and the 850 mb temperatures at OAK rose to as high as 26^{o}C on September 19. Along with this rapid ridging, peak ozone concentrations in all parts of the SJV exceeded 100 ppb and rose as high as145 ppb in the southern valley on the 19th. The 4-day period from September 17 through 20 proved to be a very good IOP opportunity. By September 21, the ridging effect was again interrupted as troughing over the northern Rockies dug back into Nevada and towards California, thus causing 500 mb heights to fall on the afternoon of the 21st and OAK 850 mb temperatures to drop 12^{o}C.

Figure2-15 shows the progression of the 500 mb height pattern during the final week of September and the first few days of October 2000. A negative tilting trough extending from Northern California to a low centered near Hudson Bay ended the IOP conditions on September 21. The trough continued to affect the project area for several days. This system developed into a strong low over the central Rockies by the 23rd that effectively moved the major trough into the Inter-Mountain area. This opened the door once again for the building of high pressure on the West Coast. However, the West Coast ridging was relatively weak and somewhat diffuse. The OAK 500 mb heights and 850 mb temperatures did increase somewhat on the 26th, and some peak ozone readings did reach 100 ppb around Fresno on that day, but then another short wave trough moved out of the Gulf of Alaska influencing conditions in California on the 28th and 29th. This effectively reduced ozone concentrations once again and caused a fall of the 850 mb temperature and 500 mb surface at OAK. As the short trough filled and moved out of the area to the southeast, another lobe of the eastern Pacific ridge once again filled into the Southwestern U.S. by the afternoon of the 29th. The OAK 850 mb temperature increased rapidly once again peaking at 21^{o}C on October 1, while the OAK 500 mb height increased to a maximum of

5,880 m. At the same time, ozone concentrations increased in all areas of the SJV, leading to exceedances of both the State and Federal Standards during the September 30 through October 2, 2000 IOP.

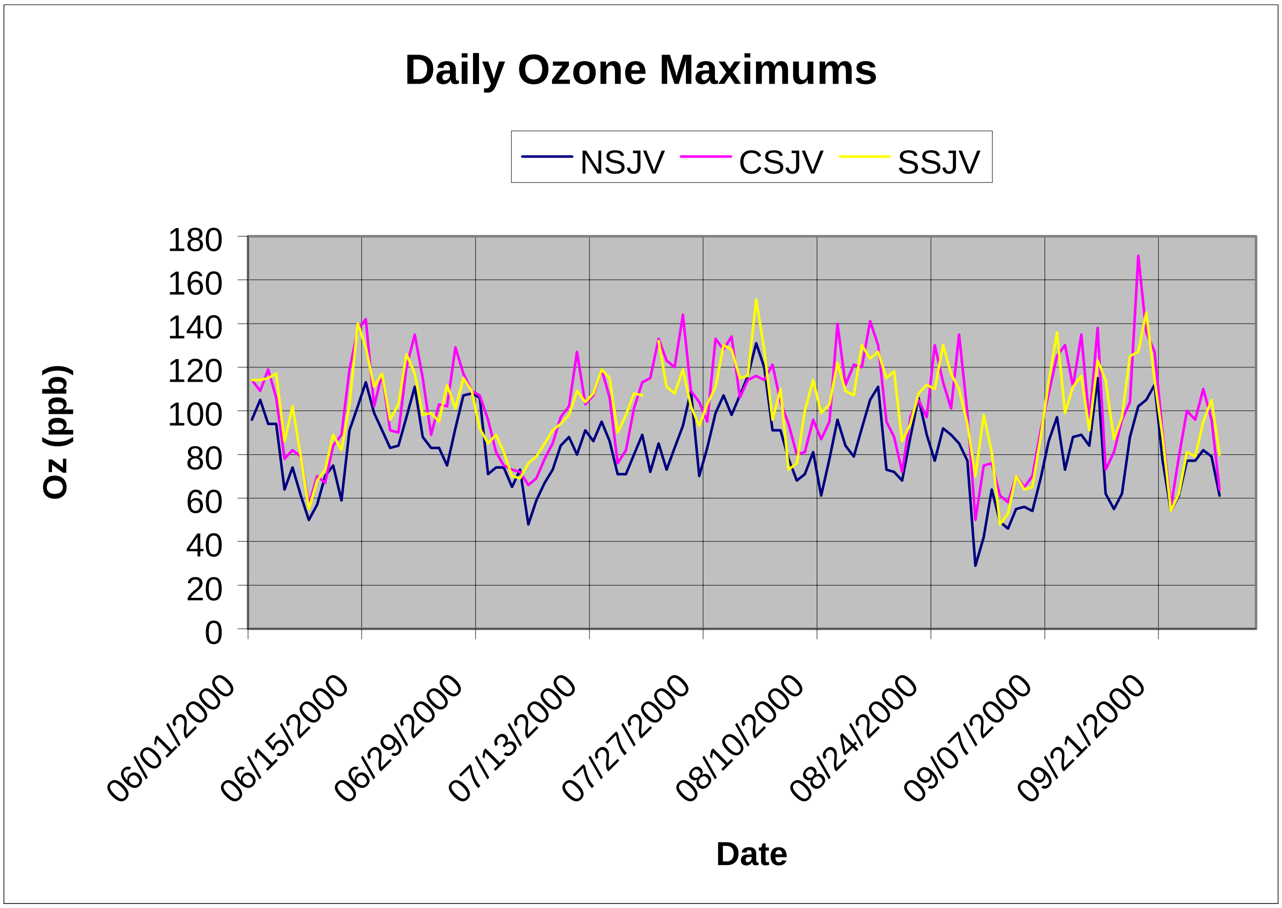
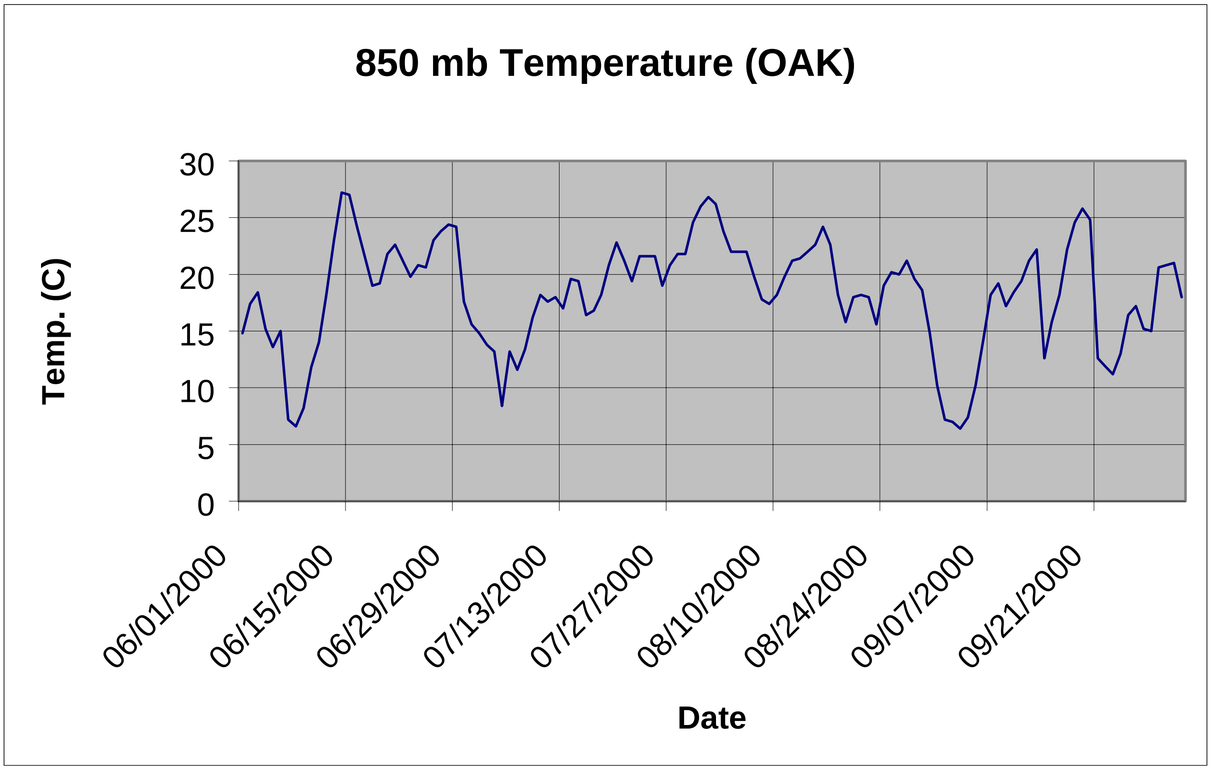


Figure 2-1. Daily Peak Ozone Concentrations in San Joaquin Valley During CCOS 2000 Field Program



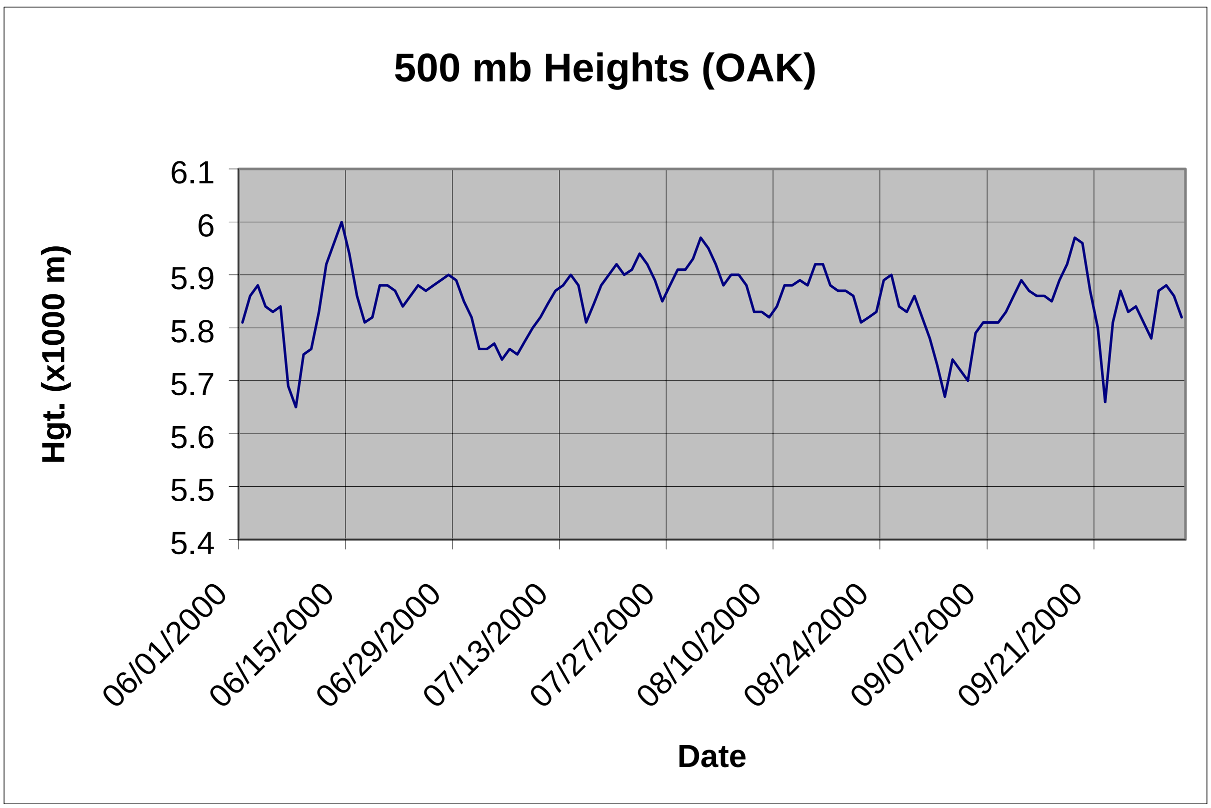
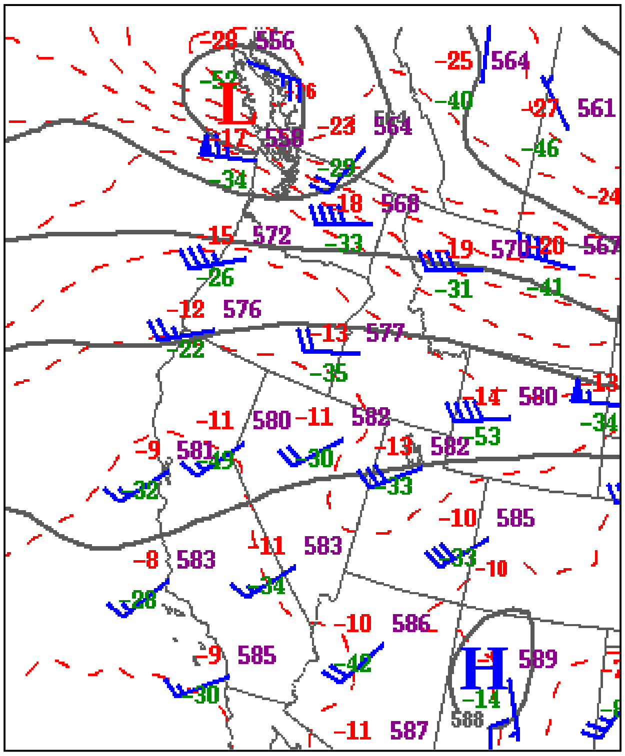


Figure 2-2. Afternoon 850 mb Temperatures and 500 mb Heights Measured Daily at Oakland NWS Station During CCOS 2000 Field Program



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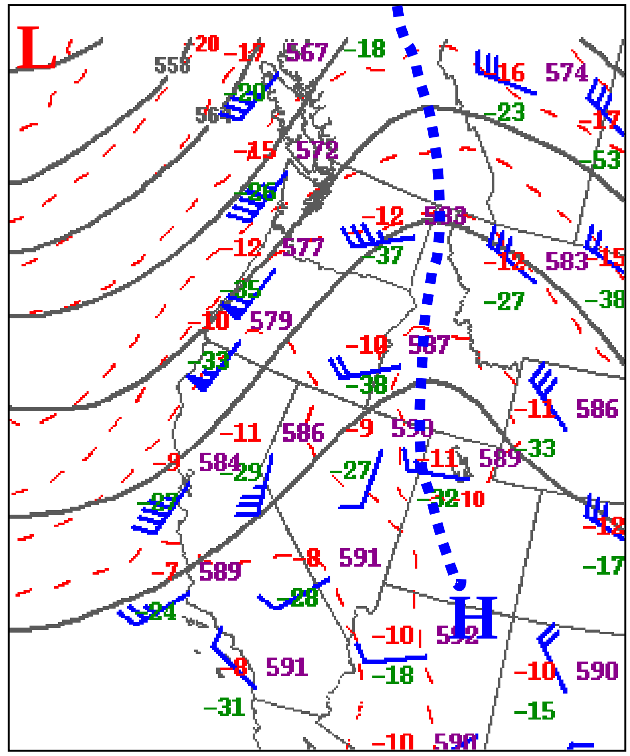

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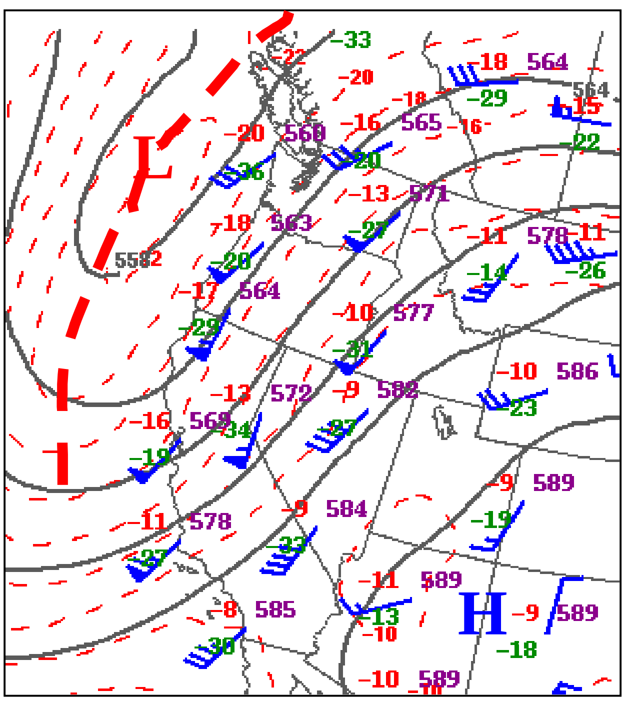

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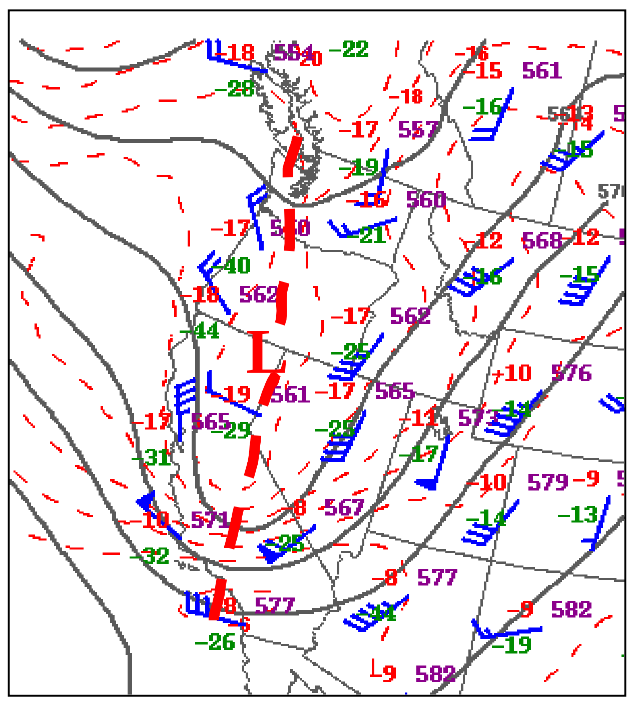


6/08/00

Figure 2-3. 500 mb Constant Pressure Charts, 1600 PST for June 1, 4, 7 & 8, 2000
(Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

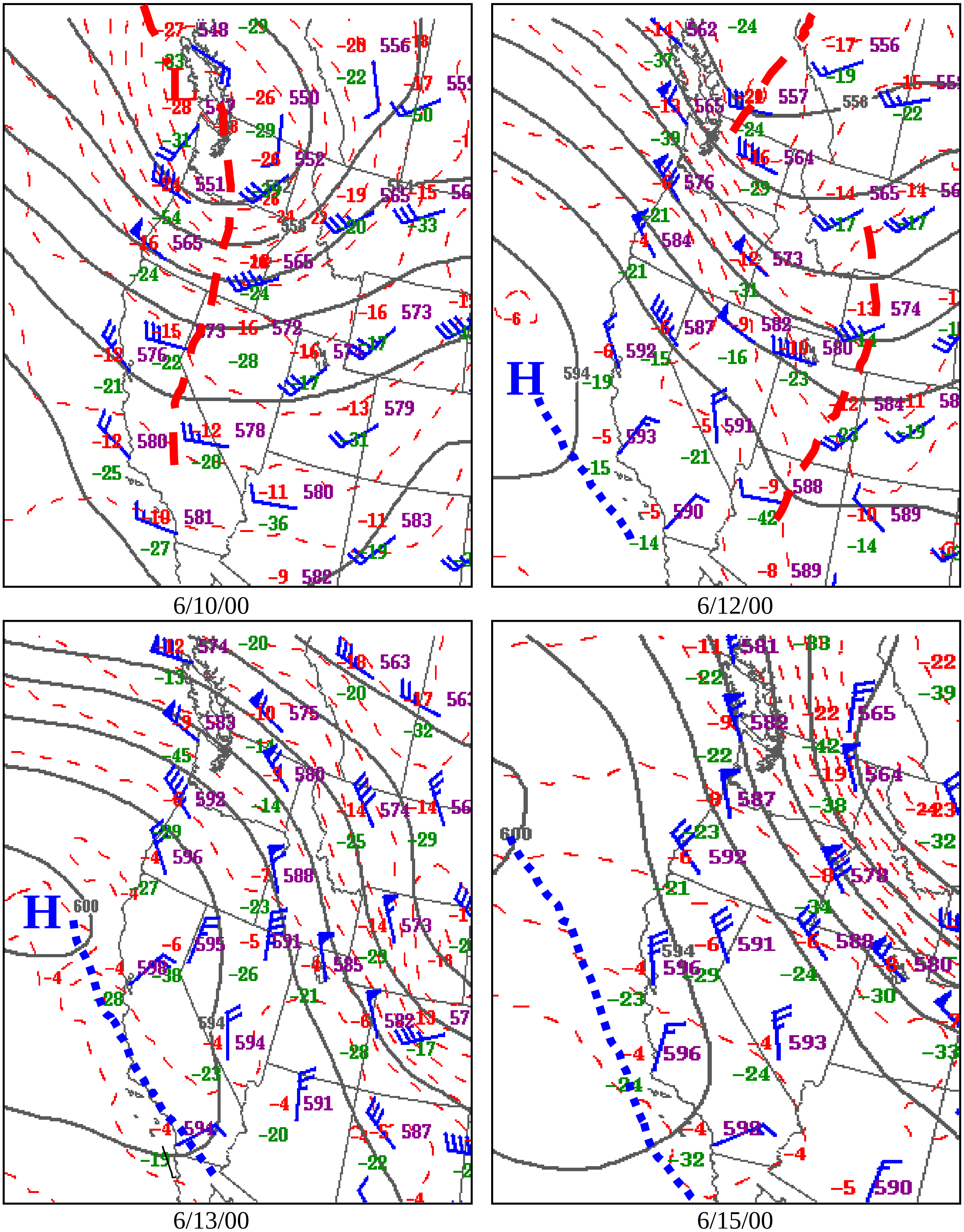


Figure 2-4. 500 mb Constant Pressure Charts, 1600 PST for June 10, 12, 13 & 15, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

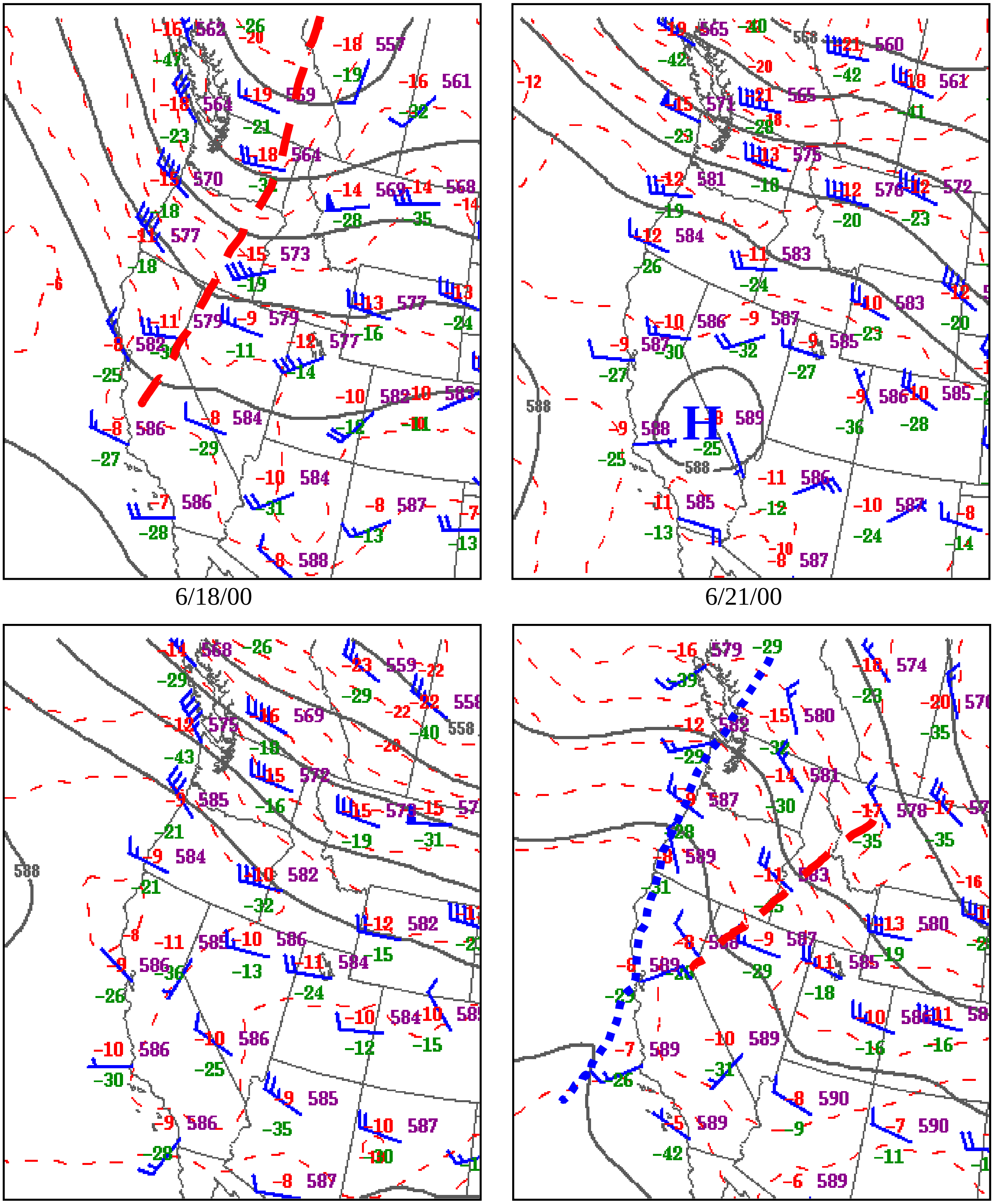


Figure 2-5. 500 mb Constant Pressure Charts, 1600 PST for June 18, 21, 23 and 27, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

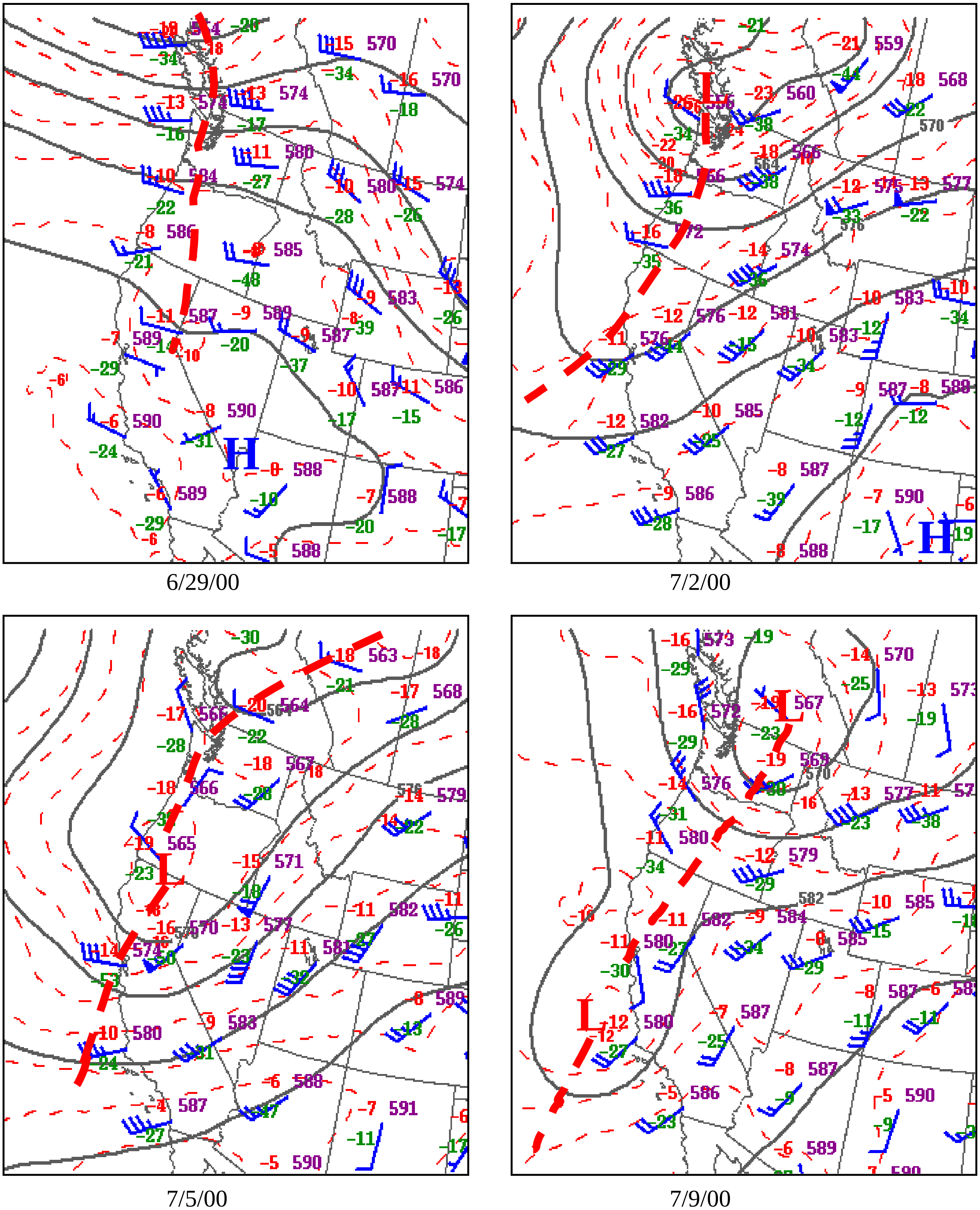


Figure 2-6. 500 mb Constant Pressure Charts, 1600 PST for June 29, July 2, 5 and 9, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

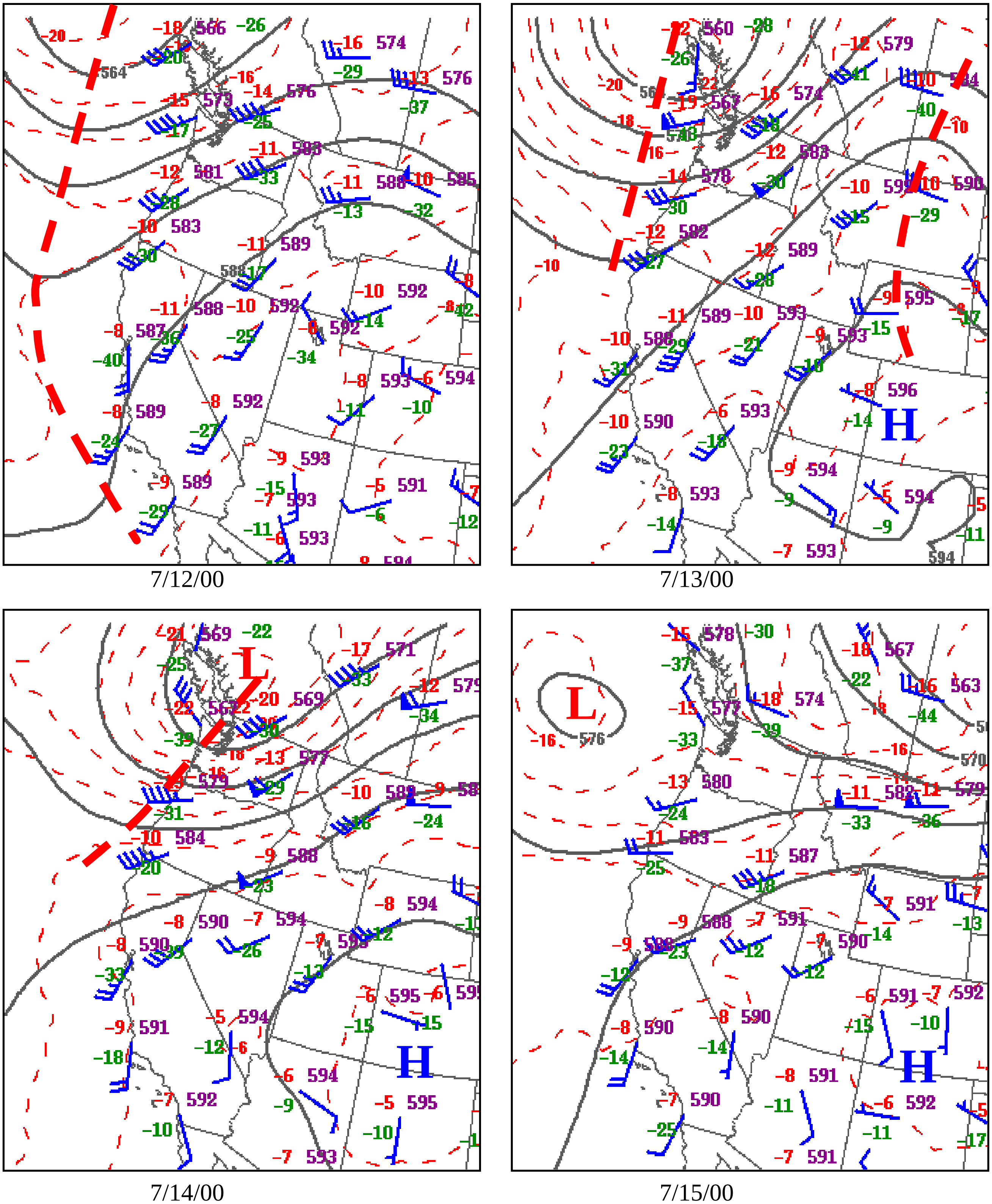


Figure 2-7. 500 mb Constant Pressure Charts, 1600 PST for July 12, 13, 14 and 15, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

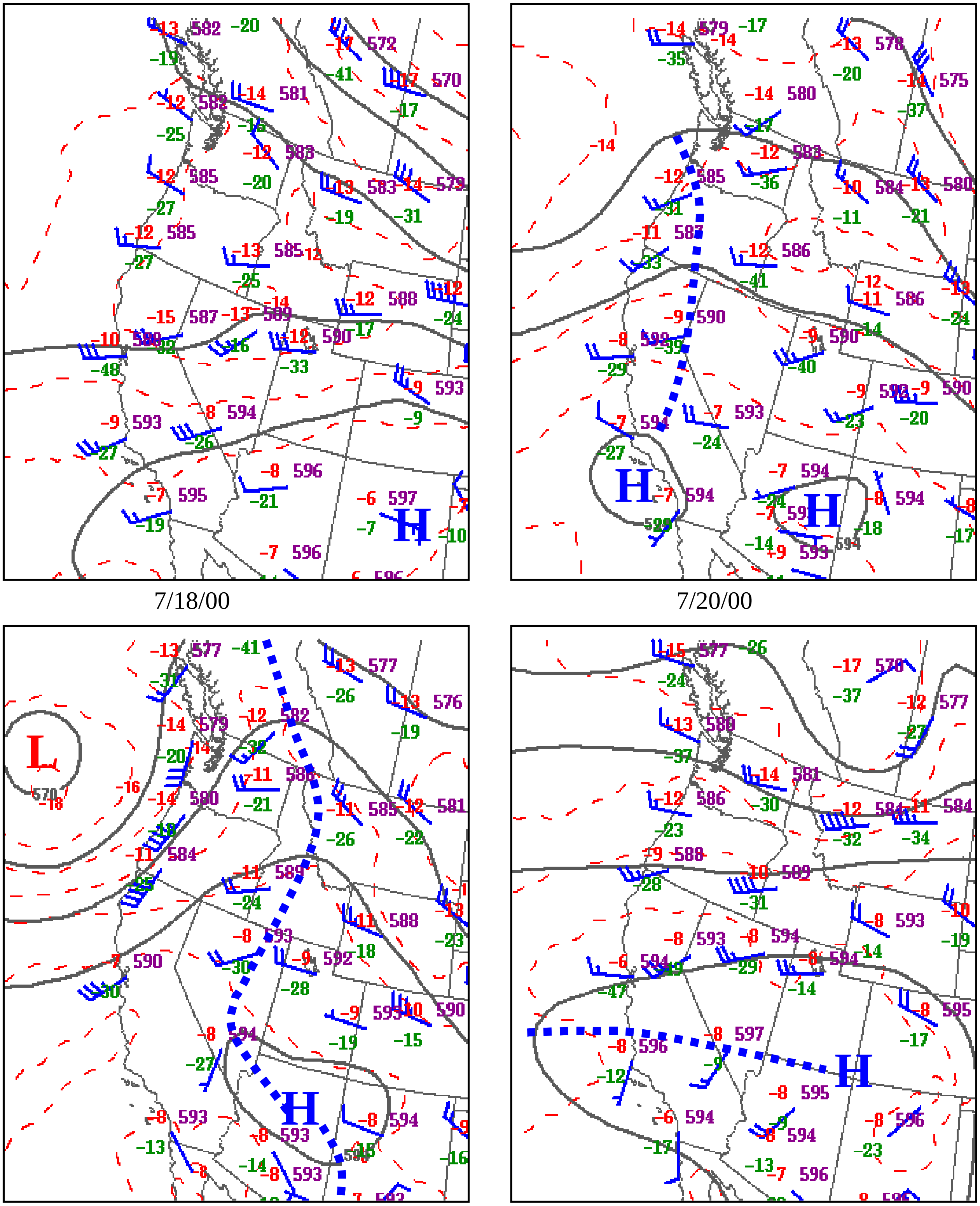


Figure 2-8. 500 mb Constant Pressure Charts, 1600 PST for July 18, 20, 21 and 23, 2000
(Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

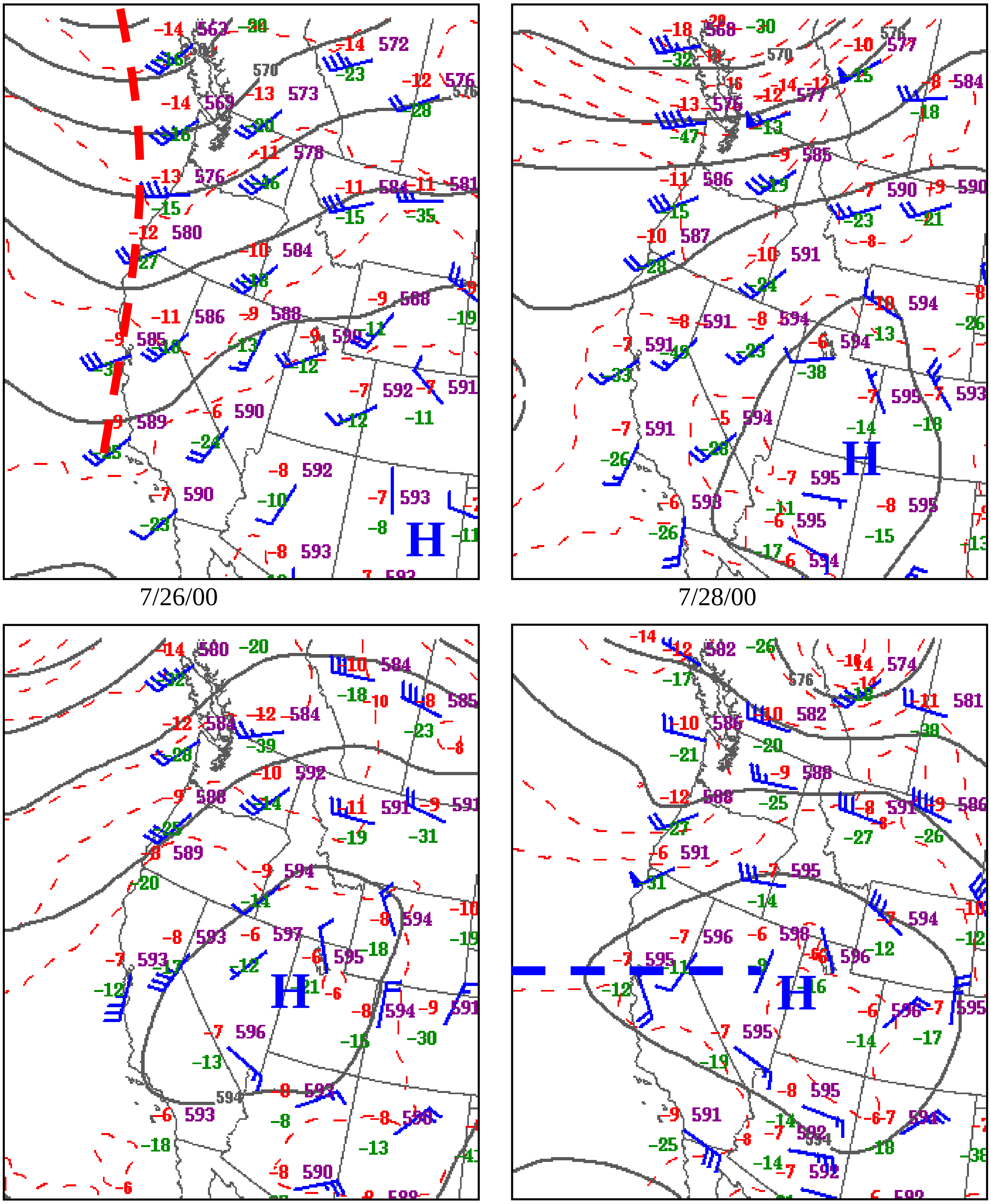


Figure 2-9. 500 mb Constant Pressure Charts, 1600 PST for July 26, 28, 30 and August 1, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

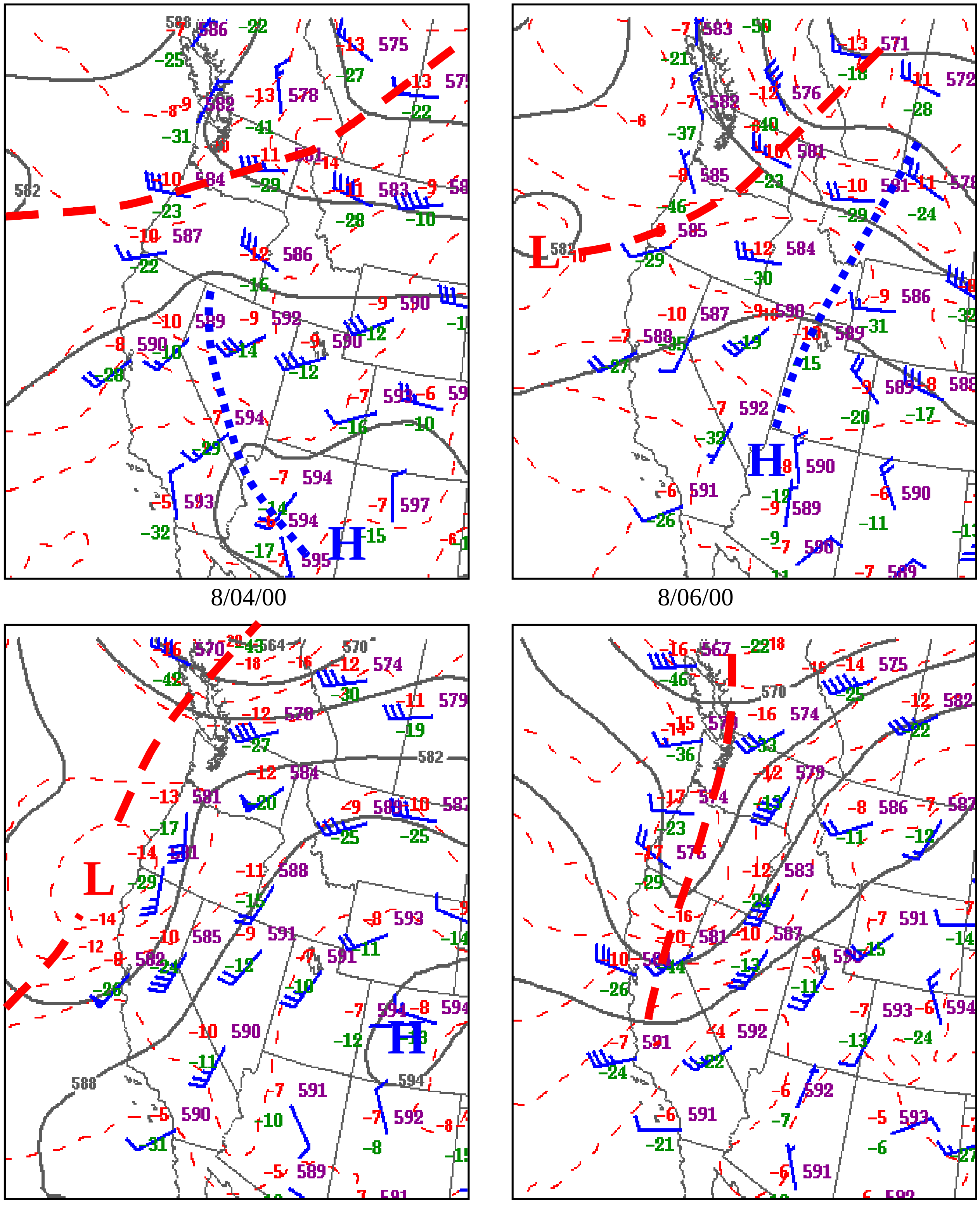


Figure 2-10. 500 mb Constant Pressure Charts, 1600 PST for August 4, 6, 9 and 10, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

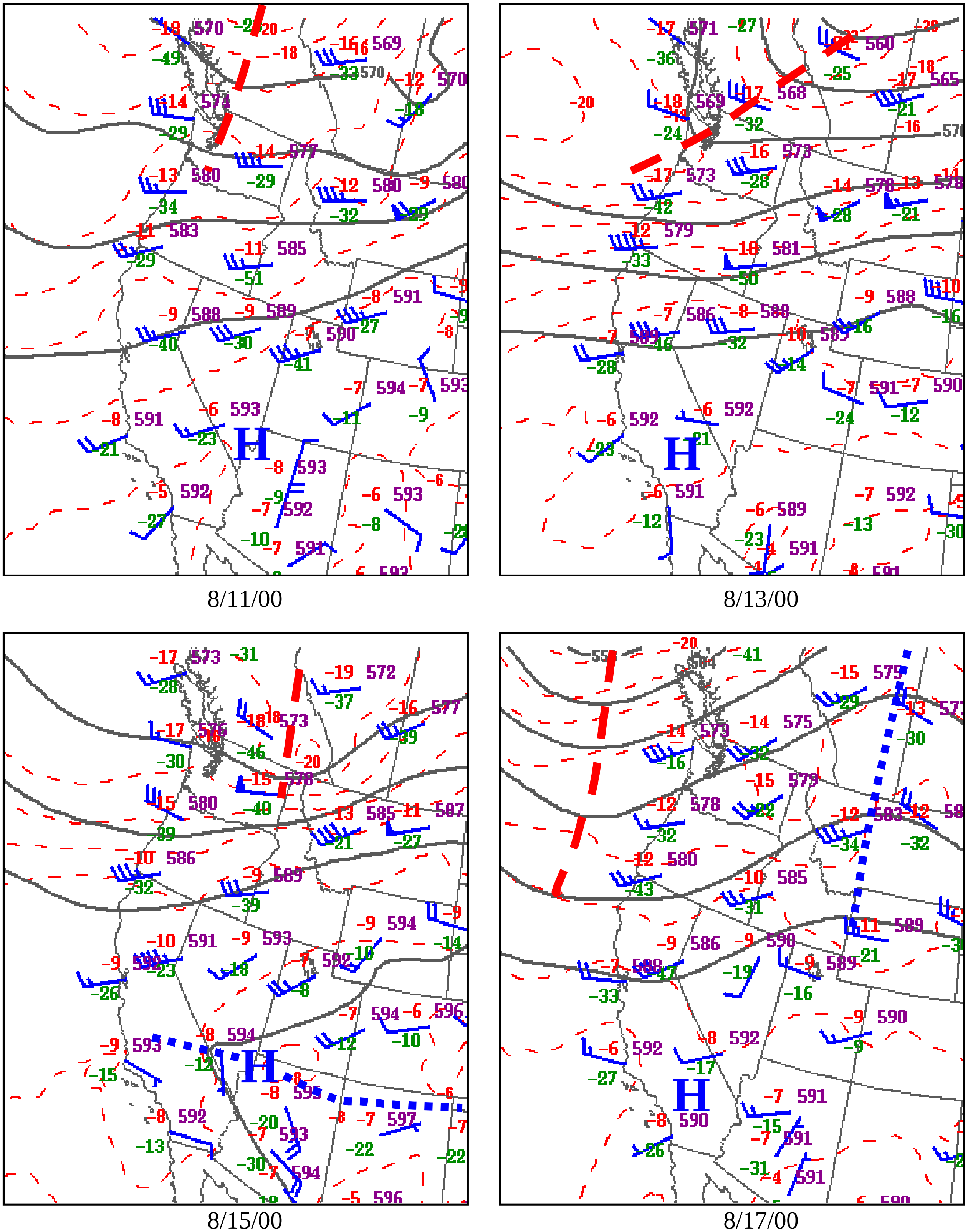
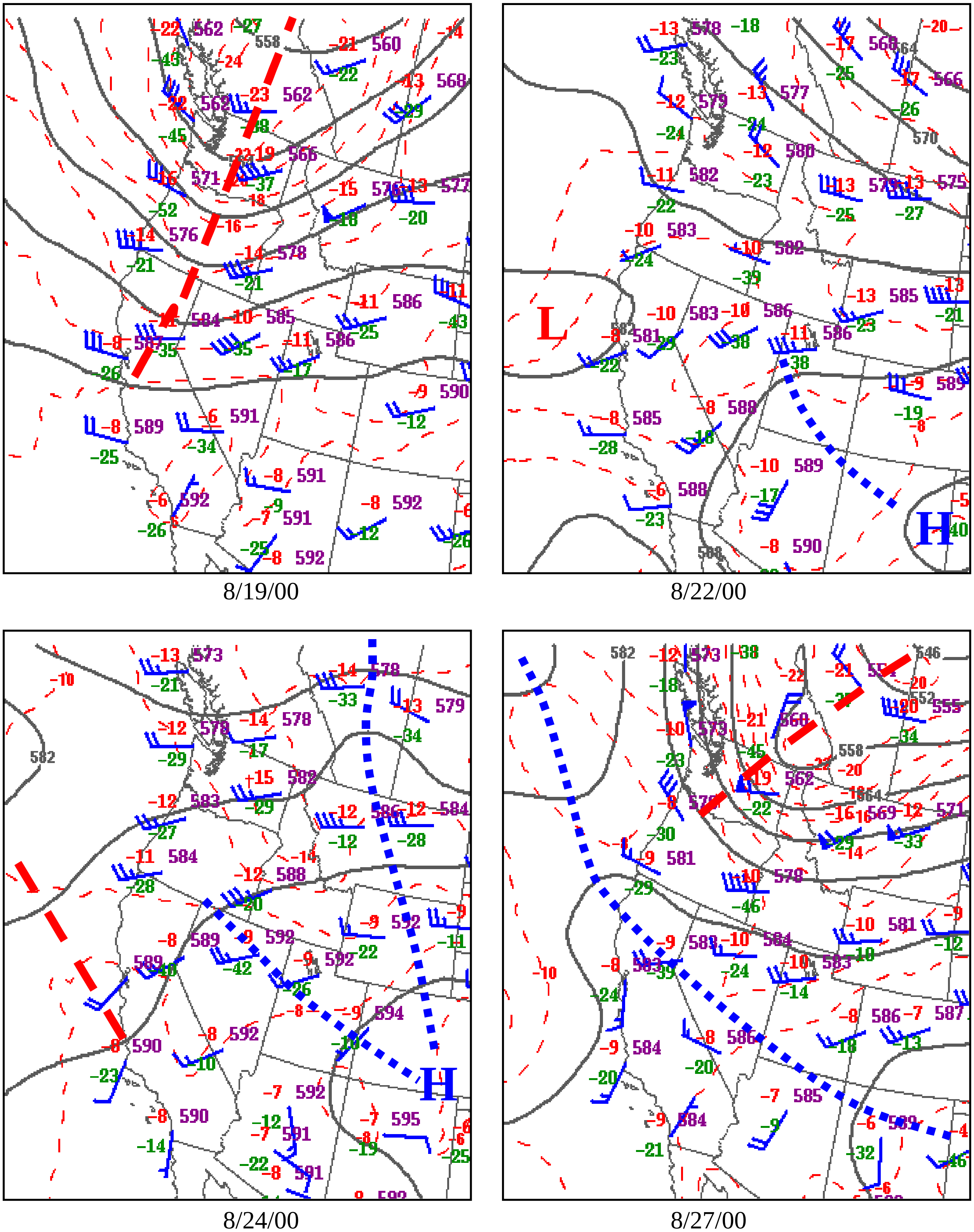
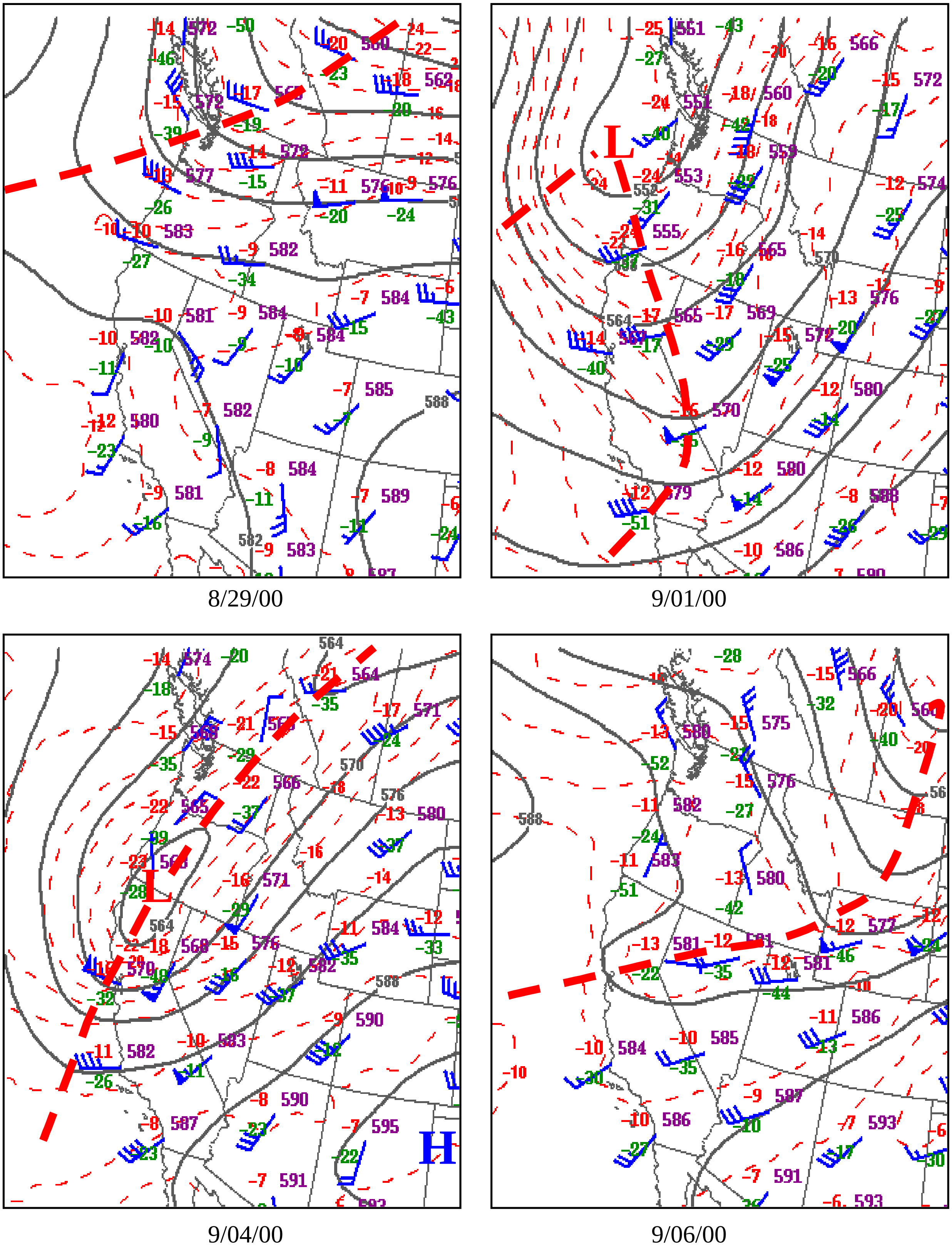


Figure 2-11. 500 mb Constant Pressure Charts, 1600 PST for August 11, 13, 15 and 17, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)



8/19/00 8/22/00 8/24/00 8/27/00

Figure 2-12. 500 mb Constant Pressure Charts, 1600 PST for August 19,22,24 and 27, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)



8/29/00 9/01/00

9/04/00 9/06/00

Figure 2-13. 500 mb Constant Pressure Charts, 1600 PST for August 29, September 1, 4, and 6, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

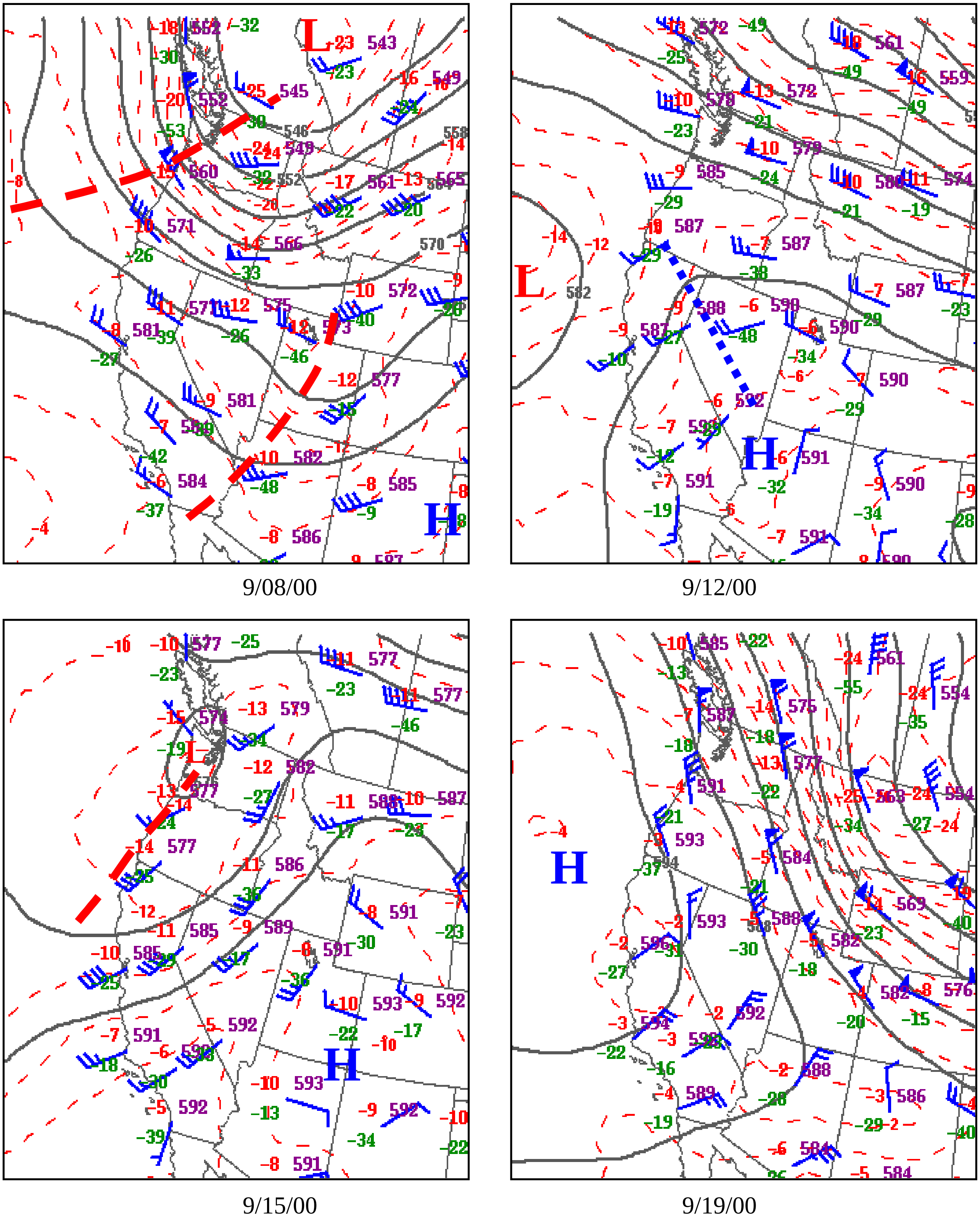
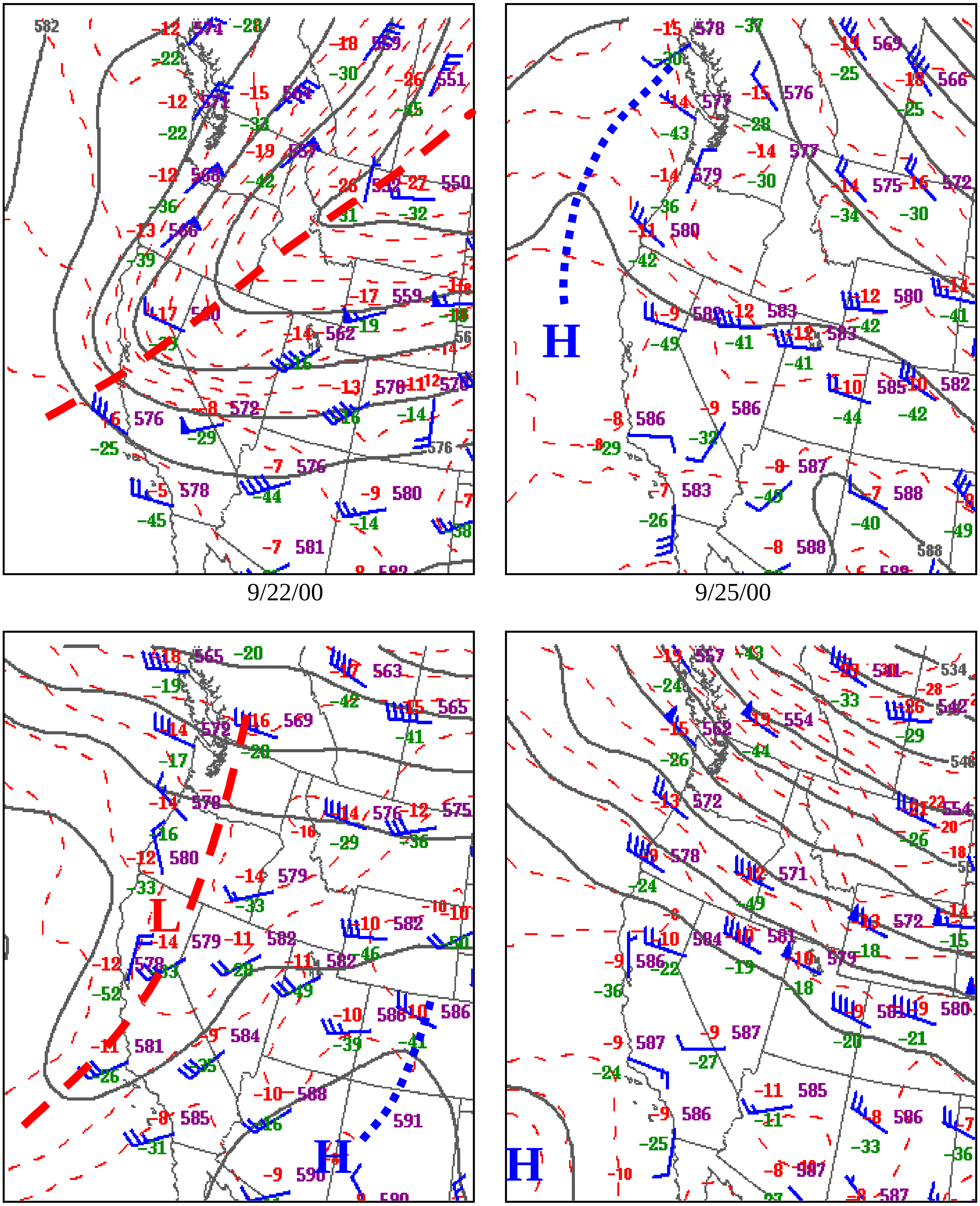


Figure 2-14. 500 mb Constant Pressure Charts, 1600 PST for September 8, 12, 15 and 19, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)



9/22/00 9/25/00 9/28/00 10/01/01

Figure 2-15. 500 mb Constant Pressure Charts, 1600 PST for September 22, 25, 28 and October 1, 2000 (Dashed line depicts trough, dotted line depicts ridge) (From NWSSPC, 2001)

3.0 BOUNDARY LAYER FLOW CHARACTERIZATION

Local terrain-induced winds are superimposed on the synoptic scale wind-field to produce the observed wind-fields in the San Joaquin Valley (SJV) and Sacramento Valley (SV). Differential heating between the ocean, coastal plains, and interior valleys produces an on-shore flow. During stable atmospheric conditions, marine air is funneled into the Central Valley through the lower gaps in the coastal ranges; namely the Carquinez Strait area and Altamont Pass, and then directed upvalley (southeast in the SJV and northwest in the SV) parallel to the longitudinal axis of the Valley. In general, air flowing into the Central Valley through the Carquinez Strait diverges with the greater volume directed into the SJV with a portion directed into the Sacramento Valley. The upvalley flow is modified by upslope winds along the Sierra slopes and, to a lesser degree, the coastal ranges. This upslope flow provides a ventilation mechanism. Valley inflow is further compensated by outflows at the Valley's southern end in the case of the SJV and the northern end in the SV.

At night as a surface temperature inversion forms, the surface boundary layer air is decoupled from air aloft causing low-level air parcels to accelerate horizontally forming a nocturnal jet that can reach speeds as great as 30 m/s. Peak velocities generally occur about 300 m-agl. Outflow at the Valley extremes is inhibited as nighttime radiation cooling continues to stabilize the lower atmosphere, eventually upsetting the air mass balance. The result is two-fold; horizontal convergence develops at low levels causing vertical divergence aloft in the Valley, and at least major one eddy regularly forms in the SJV in the vicinity of Fresno. Other eddies may form as well, in particular, in the southern portion of the SV and in the Bakersfield area. The eddy provides a mechanism for recirculating pollutants within the Valley whereas the divergence aloft provides ventilation.

In this section, two major features--the nocturnal jet and early morning eddy occurrences during the two CCOS 2000 modeling periods are examined. The timing and magnitude of these phenomenons are compared for these periods with each other and with the AUSPEX/SJVAQS.

3.1 San Joaquin Valley

The nocturnal wind jet was first observed in the SJV by Willis and Williams (1974) who conducted a brief National Weather Service study with winds aloft measurements, then was expanded upon by other studies (Morgan, 1974; Smith et al., 1981, and Blumenthal et al., 1985. An upper-air monitoring network of 25 sites in the SJV was operated during AUSPEX/SJVAQS (Thuillier, 1992; and Lehrman, et al., 1994) that provided sufficient temporal and spatial resolution to characterize the three-dimensional structure of the nocturnal jet. **Table 3-1** summarizes the nocturnal jet characteristics measured by balloon-based soundings at two sites in the network, Mariposa Reservoir and Visalia. The table contains data for the two-modeling AUSPEX/SJVAQS episodes (July 27 to 29 and August 3 to 6 (no measurements were made the evening of August 6). Peak jet velocities were relatively consistent from day to day but different at the two sites. Peak speeds ranged from 12 to 14 m/s at Mariposa Reservoir and 7 to 10 m/s at Visalia. It should be noted that the soundings were taken at 3-hour intervals restricting the time-resolution but, as can be seen in the table, peak velocities generally occurred after nightfall and prior to midnight.

Table 3-1. Nocturnal jet characteristics during AUSPEX/SJVAQS

Date	Mariposa Reservoir			Visalia		
	Time of Peak	Height	Velocity	Time of Peak	Height	Velocity
(evening of)	(PST)	(m-agl)	(m/s)	(PST)	(m-agl)	(m/s)
July 27-28	24	250	12.4	24	400	7.2
July 28-29	21	225	12.0	21	250	9.8
August 3-4	21	125	12.3	21	170	8.6
August 4-5	21	200	13.7	21	220	8.8

From Lehrman, et al. (1994)

The most pronounced eddy forms in the early morning to the south of Fresno on a frequent basis, and can develop to the point that the scale of recirculation covers the entire central and northern areas of the SJV; depending upon regional and synoptic-scale pressure gradients. The 1990 AUSPEX/SJVAQS measurements suggest the eddy initially forms at 500 m or below and can develop through a layer up to 1000 m deep. **Table 3-2** summarizes the characteristics of the Fresno eddy observed during AUSPEX/SJVAQS. It should be noted that the soundings that the table was derived from were taken at 3-hour intervals that again limits the operational time resolution.

Table 3-2. 1990 eddy characteristics derived from
Visalia rawinsonde measurements

Date	Start Time (PST)	Duration (hrs)	Max. Depth (m-agl)
July 27	06	3	450
July 28	06	3	650
July 29	06	3	850
Aug 3	03	6	400
Aug 4	03	6	600
Aug 5	03	7	1300
Aug 6	00	12	1600

From Lehrman, et al. (1994)

With the exception of August 6, the eddy formed between midnight and 06. During the July 1990 episode, the eddy persisted for about 3 to 5 hours. During the August episode, the eddy persisted for 6 to 8 hours. Lehrman et al. reported that the jet started to develop as usual on the evening of August 5 but prior to midnight the flow switched to southeast. The eddy developed to the extent that it encompassed the entire northern half of the SJV.

Radar wind profilers operated by NOAA at Visalia, in the central SJV, and Waterford, at the northern end of the SJV, were examined to determine the nocturnal jet and eddy characteristics during CCOS. The Visalia site was at the airport, approximately 70 km south of Fresno; whereas, in 1990 the site was east of the city. The Waterford profiler was located approximately 25 km east of Stockton, which is usually outside of the influence of the Fresno eddy as was the AUSPEX/SJVAQS Mariposa Reservoir site about 50 km to the southeast. Two CCOS episodes consisting of nine days were considered: July 30 to August 2, and September 17 to 21. Time series plots showing the along-valley wind component (northwest to southeast) for the nine days are provided in Appendix B of this report.

The onset time of the nocturnal jet, duration, and maximum speed at Visalia are shown in **Table 3-3**. The defining speed for characterizing the jet was 6 m/s. As can be seen from the table, during the July-August episode the nocturnal jet developed on three of the four evenings. On July 30 and July 31, peak observed winds were 11.1 to 11.4 m/s and occurred at 300 m-agl. Peak velocities measured in the jet occurred between 19 and 20 PST. On August 2, the peak wind speed was 9.5 m/s measured at 400 m-agl. Wind velocities in the jet remained > 6 m/s for 6 hours peaking at 23 PST on the evening of July 30 to 31 and July 31 to August 1. No wind speeds greater than 6 m/s were measured at Visalia on the evening of August 1. A jet developed on the evening of August 2 to 3 but later and weaker than earlier in the episode.

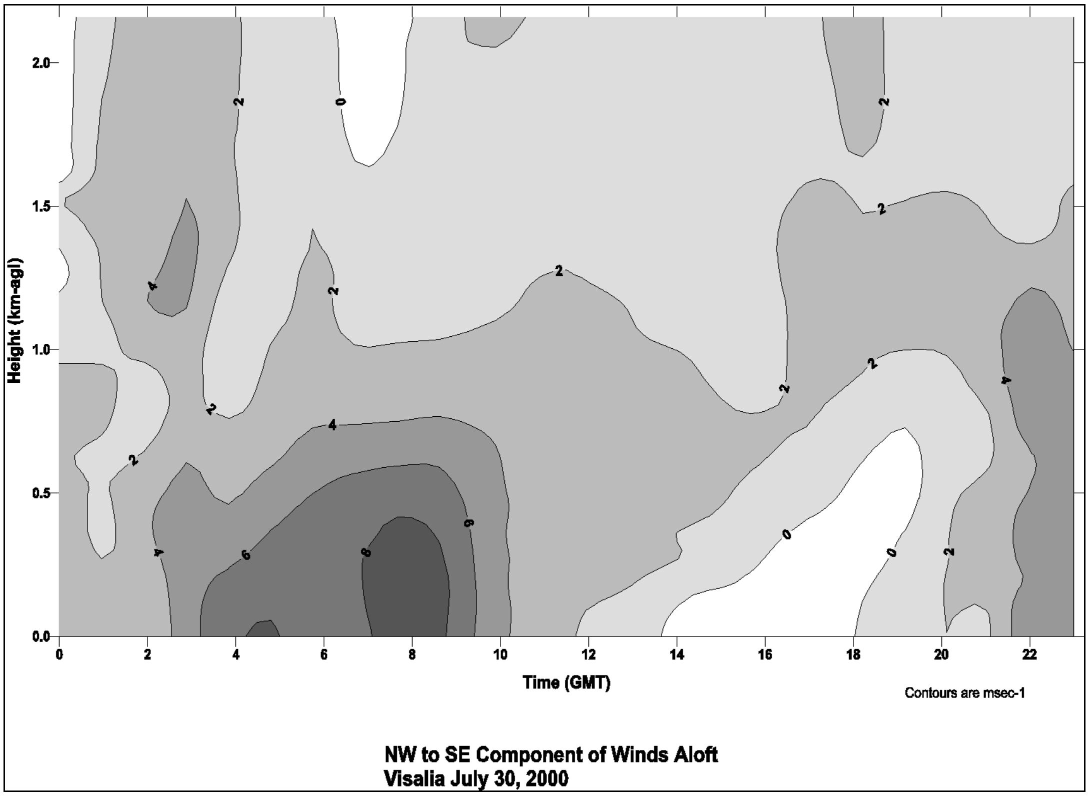
The Waterford measurements are summarized in Table 3-3 as well. The jet was observed during the first three evenings of the episode peaking earlier in the evening than at Visalia and at somewhat reduced speeds. Strong upvalley winds were measured through the afternoon and evening of August 3.

Table 3-3. Nocturnal jet characteristics during 2000 CCOS

Date (evening of)	Waterford Duration* (hrs)	Waterford Time of Peak (PST)	Waterford Height (m-agl)	Waterford Velocity (m/s)	Visalia Duration* (hrs)	Visalia Time of Peak (PST)	Visalia Height (m-agl)	Visalia Velocity (m/s)
July 29-30	5.5	22	120	9.6	6	23	300	11.1
July 30-31	3	21	180	9.5	6	23	300	11.4
July 31-Aug 1	3	19	120	10.3	no jet formed			
Aug 1-2	strong winds thoughout afternoon and night				4	01	400	9.5
Sept 16-17	3.5	00	180	8.6	1	20	400	9.1
Sept 17-18	no nocturnal low-level jet observed				no nocturnal low-level jet observed			
Sept 18-19	no nocturnal low-level jet observed				4	21	350	8.0
Sept 19-20	no nocturnal low-level jet observed				no nocturnal low-level jet observed			
Sept 20-21	moderate to strong NW winds all period				2	22	450	9.4

* Duration above 6 m/s in the layer 100-500 meters above ground

The jet developed on the first two evenings of the episode in a manner consistent with the SARMAP conceptual wind flow model based on 1990 measurements, and in concert with the Fresno eddy development. The time-height cross section of the along-the-valley wind component at Visalia for the <u>24 hour period starting at 16 PST (00 GMT)</u> on July 29 is shown on the top panel of **Figure 3-1**. Positive isotachs are upvalley flow (northwest to southeast). Negative isotachs are downvalley directed. As depicted in the figure, the flow aloft was generally light in the 2 to 3 m/s range. The nocturnal jet is seen in the evening (03 to 09 GMT) below 500 meters followed by light reverse flow in the lower 600 meters between (14 and 18 GMT). By afternoon northwest flow has been reestablished. At Waterford for the same period (bottom panel of Figure 3-1), a similar jet formed but, unlike the winds at Visalia, northwest



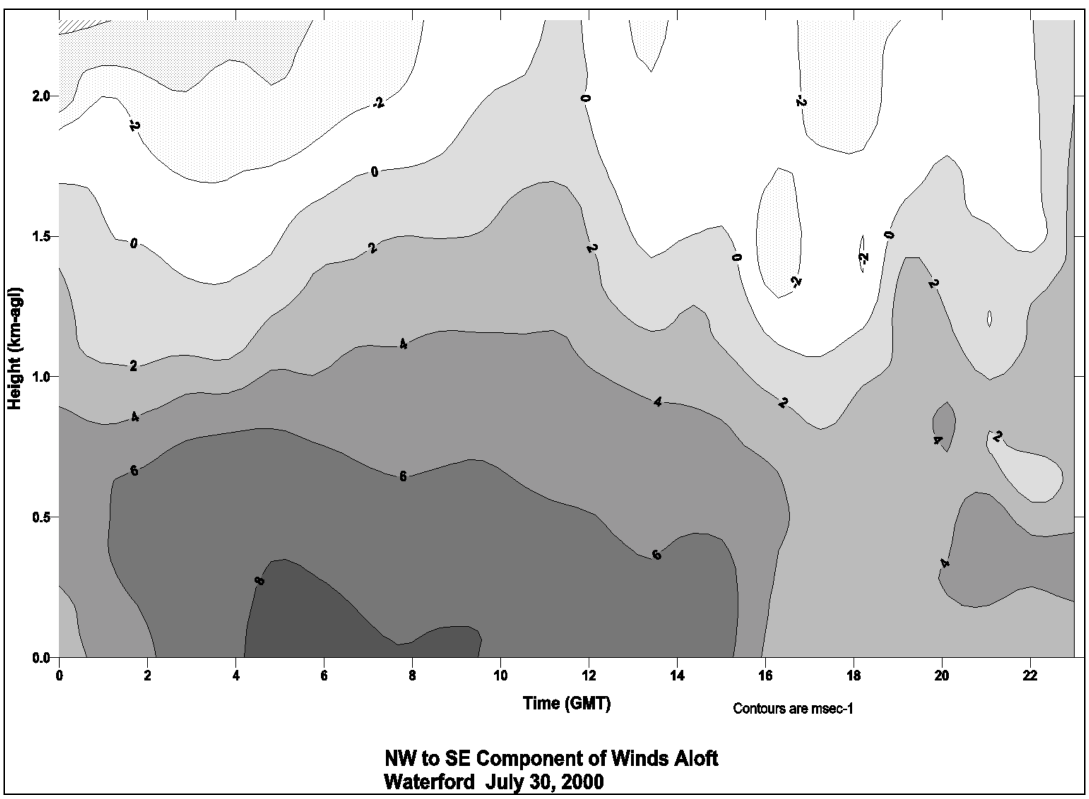


Figure 3-1. Time-height cross-sections of the along-the-valley wind component for Pleasant Grove (top) and Arbuckle (bottom) on July 30, 2000

winds continued throughout the period. This pattern repeated on the evening and morning of July 30 to 31.

The Fresno eddy is defined in our analysis by the occurrence of down-valley flow at Visalia (having a negative NW to SE component) at low levels during the forenoon period. Estimates of the onset, duration and depth of the eddy as measured by the Visalia radar profiler winds aloft are given in **Table 3-4**, and should compare with the 1990 measurements shown in Table 3-2.

As seen in the table, during CCOS the eddy developed to some extent on all four days of the July 30 to August 2 study period. The eddy development on the morning of July 30 and 31 was typical of the AUSPEX/SJVAQS observations in that the eddy began development near daybreak and persisted for several hours.

During this episode, the dominant synoptic feature, a high pressure cell over the southwestern U.S. retrograded reaching its furthest western point on August 1 before migrating eastward again. This was apparently the reason that beginning in the evening of July 31 the wind flow pattern of previous two days was disrupted and flows with a strong southerly component developed **(Figure 3-2).** The jet/eddy mechanism reformed the following day.

Table 3-4. CCOS eddy characteristics derived from Visalia radar wind profile measurements

Date	Start Time (PST)	Duration (hrs)	Max. Depth (m-agl)
July 30	06	3	450
July 31	06	3	650
August 1	normal pattern disrupted		
August 2	06	3	300
September 17	03	5	~800
September 18	03	7	*
September 19	04	6	weak and shallow
September 20	*	*	
September 21	no data		

* difficult to discern from general flows

The SJV wind patterns during the September CCOS episode were very different from the July 30 to August 2 episode and the AUSPEX/SJVAQS design modeling episodes. The Visalia and Waterford winds time-height cross-section plots in **Figure 3-3** are representative of the September episode. It is seen from the figure that 1) a moderately strong southerly-dominated wind field was present (the reader should ignore the Visalia winds from 04 to 12 GMT above 1 km keeping in mind that these are Level 0 invalidated data), 2) the upvalley or NW-SE wind component was very weak during the early evening/late afternoon when normally the strongest, and 3) winds were very light with a slight downvalley component at both sites during the morning hours. In general, winds in the boundary layer were relatively light resulting in only weak inter- and intrabasin transport.

Similar plots for the other study days are in Appendix B of this report.

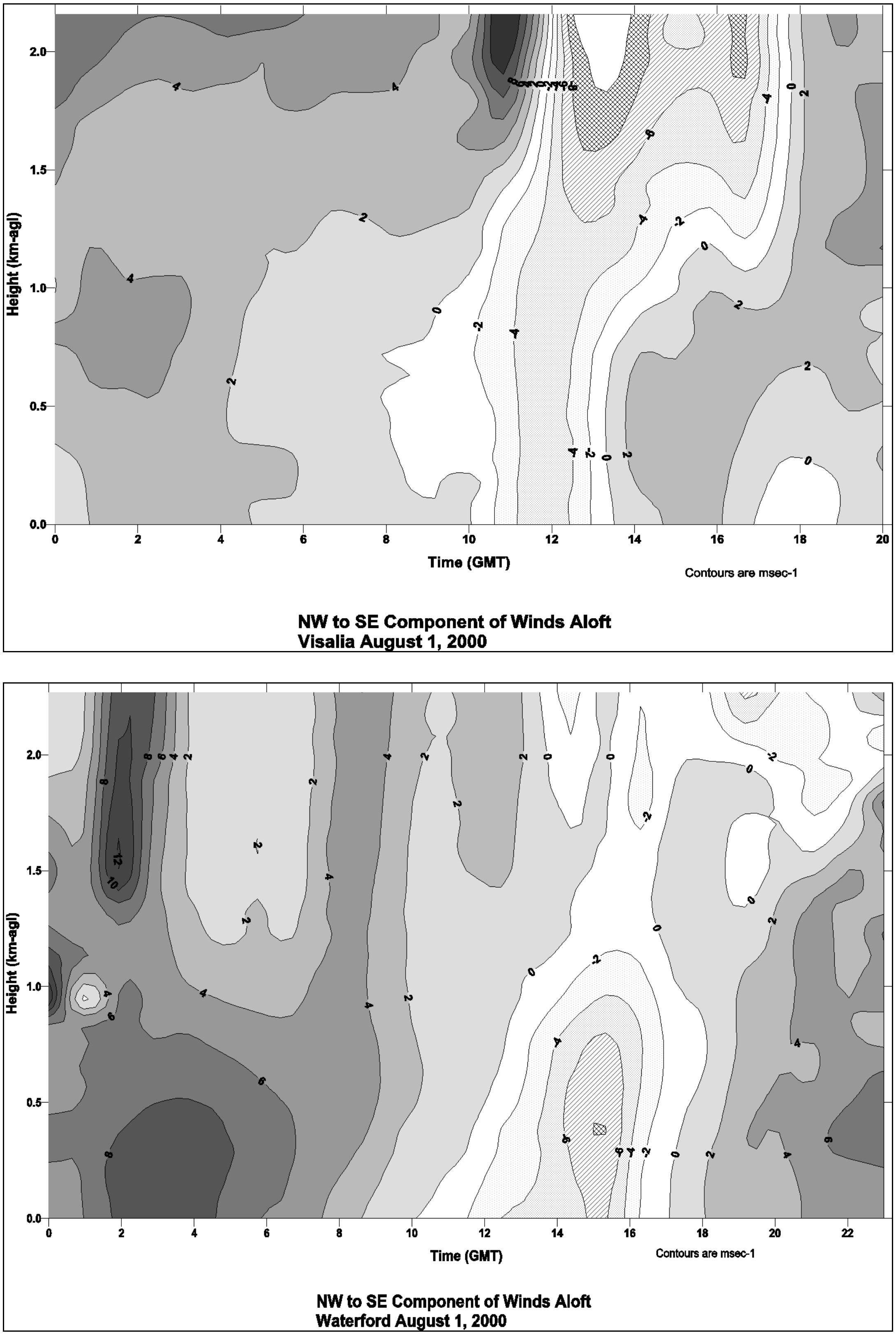


Figure 3-2. Time-height cross-sections of the along-the-valley wind component for Visalia (top) and Waterford (bottom) on August 1, 2000

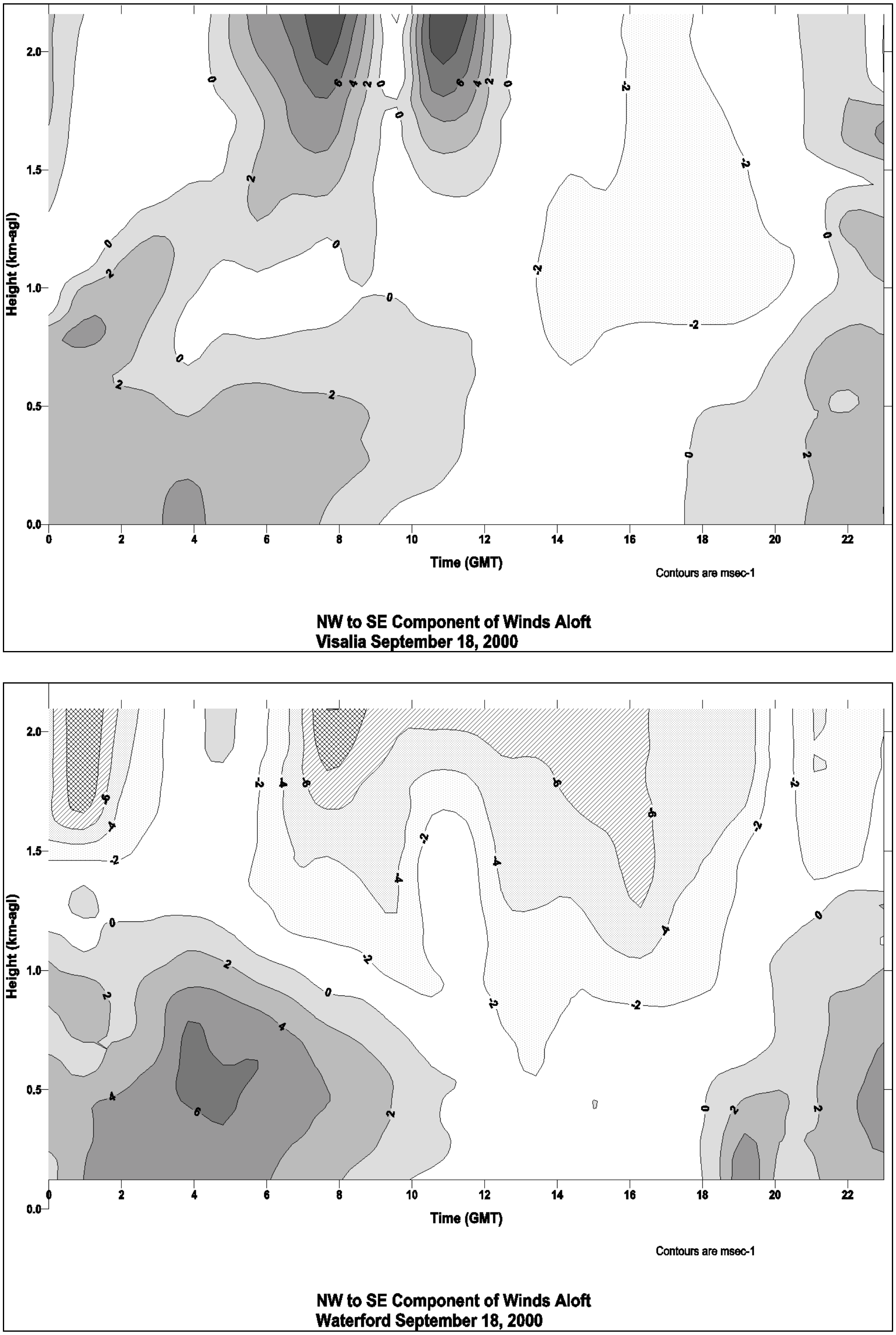


Figure 3-3. Time-height cross-sections of the along-the-valley wind component for Visalia (top) and Waterford (bottom) on September 18, 2000

3.2 Lower Sacramento Valley

Our preliminary examination of the wind field patterns in the Sacramento Valley during CCOS used invalidated NOAA radar wind profiler data from 3 sites; Sacramento, Pleasant Grove and Arbuckle. Pleasant Grove is approximately 30 km north of Sacramento. Arbuckle is on the west side of the SV approximately 70 km northwest of Sacramento. Pleasant Grove and Arbuckle are situated well into the lower Sacramento Valley where local terrain-induced winds should dominate the low-level flow pattern below 1 km. Roberts et al. (1994) and Lehrman et al. (1980) analyses of measurements in the lower SV showed that low-level winds in Sacramento to be primarily dominated by the inflow of air through the Carquinez Strait. Within the Sacramento area, winds on the west side were generally from the west, peaking in the late afternoon and continuing throughout the night. Minimum velocities were observed in the forenoon. Measurements midtown and east showed backing of the winds as terrain steered the flow upvalley.

The CCOS winds aloft during the two analysis episodes are summarized in **Table 3-5**. The data presented therein are essentially consensus winds in the lowest 500 m at 08 and 22 PST from the three monitoring sites. These specific hourly measurement times are significant in that any nocturnal jet or eddy development should be represented. Wind velocities are categorized as light, moderate or strong and the predominant wind direction is given in the table as one of the eight compass points. A complete set of time-height cross sections of the along-the-valley wind component for Pleasant Grove and Arbuckle are provided in Appendix B.

Table 3-5. Low-level flows in the lower Sacramento Valley during CCOS for select sites

Date	SAC (Wind Speed/Direction)		PLG (Wind Speed/Direction)		ARB (Wind Speed/Direction)	
	08 PST	22 PST	08 PST	22 PST	08 PST	22 PST
Jul 30	M/W	M/W	L/N	L/V	L/NW	L/V
Jul 31	M/W	M/W	L/N	L/W	L/NW	L/V
Aug 1	M/SE	S/W	M/SE	M/SE	L/V	L/NW
Aug 2	L/W	-	L/SE	-	L/SE	-
Sept 17	L/N	L/W	M/NW	L/W	S/NW	M/NE
Sept 18	L/V	M/W	L/S-SE	L/W	S/NW	S/NW
Sept 19	L/V	M/W	M/N	L/V	S/NW	S/W
Sept 20	L/E	S/SW	L/V	M/S	S/NW	S/W
Sept 21	S/SW	-	L/S	-	L/V	-

L = light velocities ≤ 3 m/s
M = moderate velocities ≤ 6 m/s
S = strong > 6 m/s
V = variable

Observe from the table that low-level winds were generally light during the July 30 to August 2 episode in the Sacramento Valley north of Sacramento as shown by the Arbuckle and Pleasant Grove winds. The winds aloft at Sacramento were westerly with moderate velocities (> 3 m/s) on July 30 to 31, the period that the jet and Fresno eddy mechanisms developed fully in the SJV.

This suggests that most of the air flowing in through the Carquinez Strait veered southeastward into the SJV with a small portion directed due east past Sacramento resulting in little or no flux into the northern SV. The limited upvalley (southeast) air movement into the Sacramento Valley is illustrated in the time-height cross sections of the along-the-valley wind component shown in **Figure 3-4**.

The wind fields appear more complex during the second episode. Morning flows at Sacramento were relatively light from September 17-20 as opposed to the moderate wind velocities observed in the first episode. On the afternoon of the 20th, the wind at Sacramento turned southwest and increased in velocity. The Arbuckle low-level winds were out of the north with high velocities often in excess of 12 m/s for most of the episode. On the evening of the 20th the winds became westerly with continuing high velocities. By the morning of the 21st, winds were light and variable. Winds measured at Pleasant Grove were generally light to moderate, exhibiting none of the strong downvalley flow occurring on the west side. **Figure 3-5**, the time-height wind cross-sections for September 19, is representative of the measurements at Pleasant Grove and Arbuckle during the episode.

It should be noted that there was no evidence in the data examined of neither significant nocturnal jet development in the southern SV or substantial eddy development. The data set examined was limited to three sites and was not subject to an intensive analysis. The complexities of the wind field warrant more detailed analysis using all the measurements available.

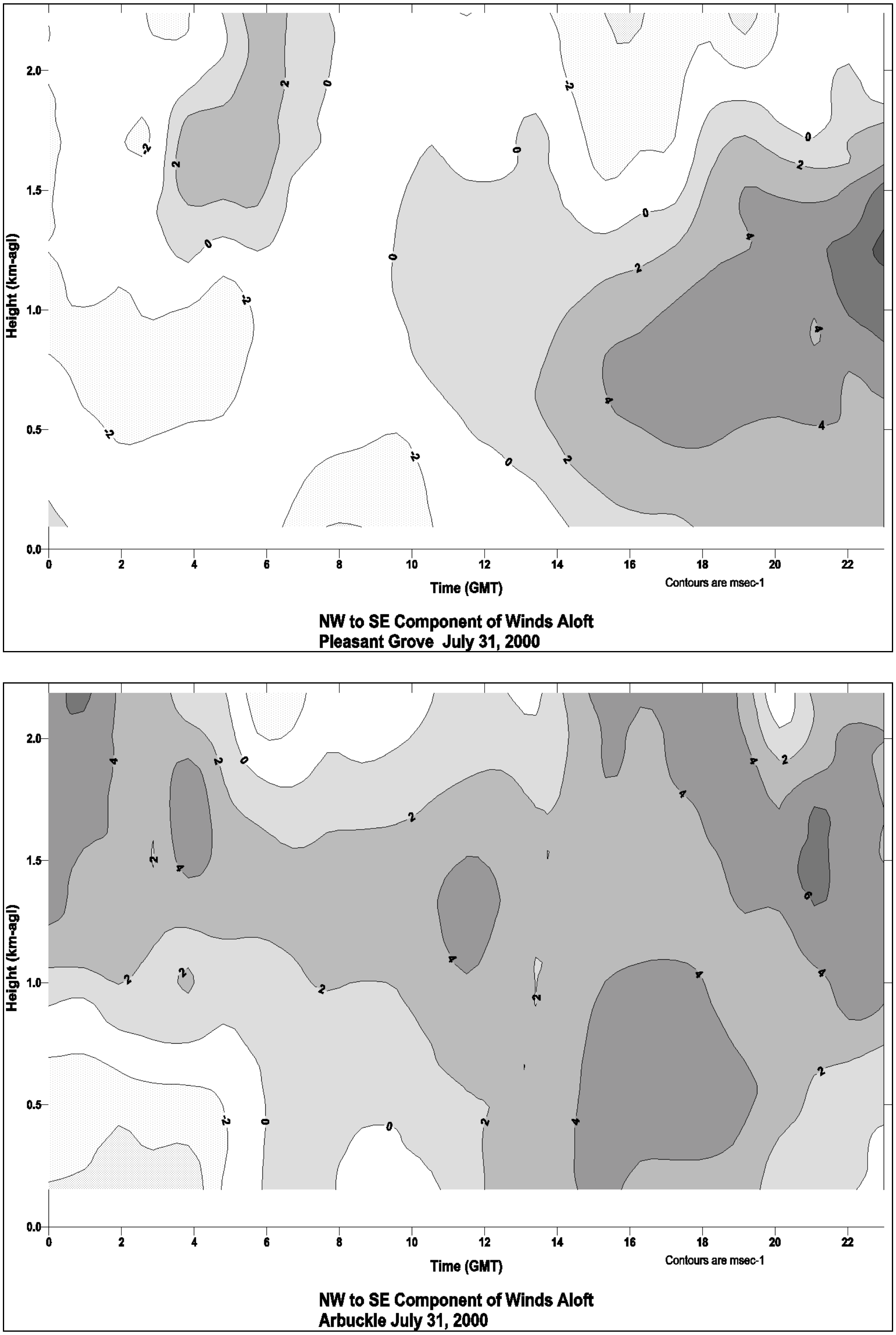
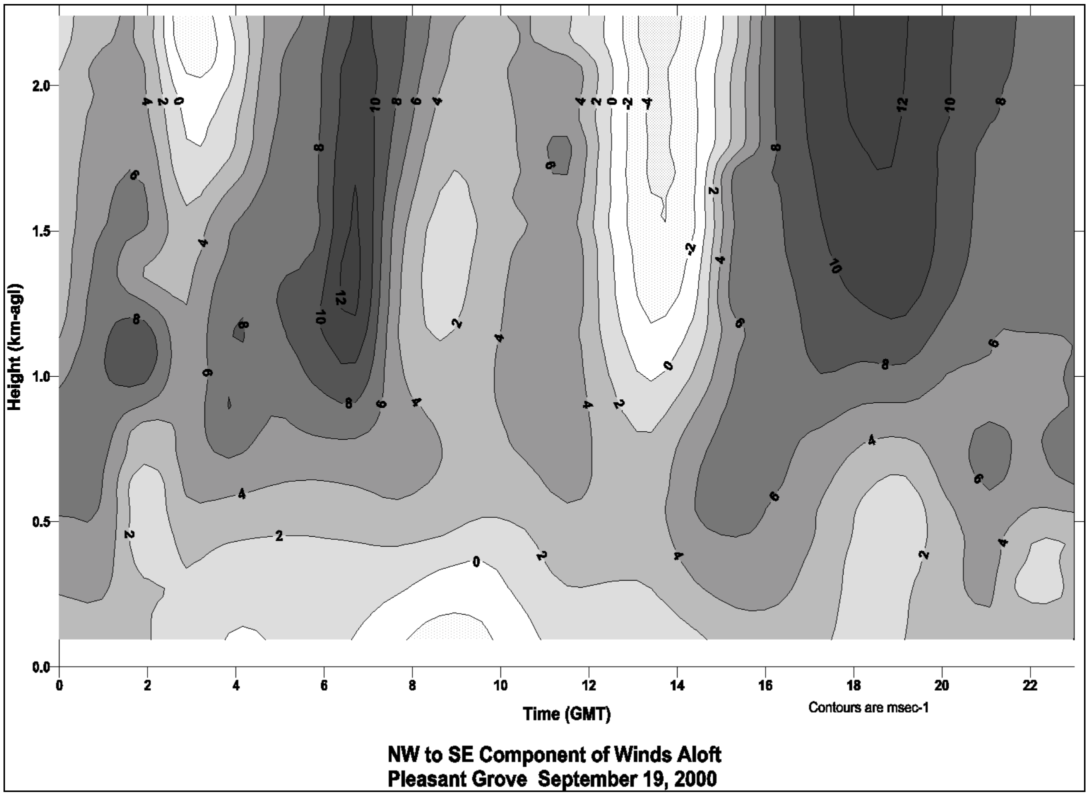


Figure 3-4. Time-height cross-sections of the along-the-valley wind component for Pleasant Grove (top) and Arbuckle (bottom) on July 31, 2000



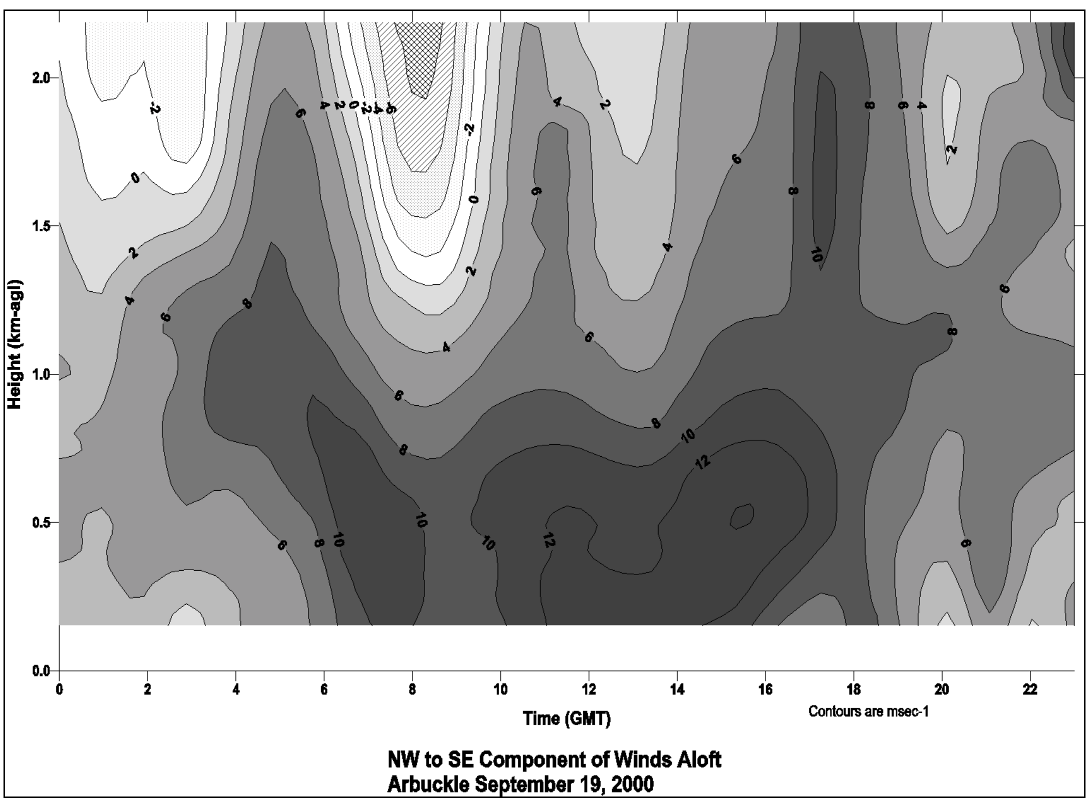


Figure 3-5. Time-height cross-sections of the along-the-valley wind component for Pleasant Grove (top) and Arbuckle (bottom) on September 19, 2000

4.0 STATISTICAL ANALYSES

4.1 Meteorological Cluster Analysis

The objectives of the cluster analysis are twofold:

1. Using a long-term (10 year) data base, determine whether the meteorological conditions conducive to high ozone levels in the CCOS study area are generally similar, or are there clear-cut differences, and

2. If the meteorological variables associated with high ozone fall into one, or more than one, grouping or clusters, are there discernible differences between the meteorology associated with the CCOS episode days and the 10-year database.

4.1.1 Methodology

June-September meteorological data were compiled for the period 1990 to 2000. Parameters were selected on the basis of the results of polling a number of scientists who have experience forecasting ozone episodes operationally. Forty-two meteorological variables were examined (See **Table 4-1**). Data were restricted to the days with no missing values. Analysis was performed for the following subsets of data: i) days with an 8-hour ozone exceedance somewhere in the 3-basin (San Joaquin Valley [SJV], Sacramento Valley [SV], San Francisco Bay [SFB]) area; ii) days with 8-hour but not 1-hour exceedance; iii) days with a 1-hour exceedance; and iv) episode days[1].

Cluster analysis is based on some metric to represent "distance" between data points, where a data point would be a vector of meteorological observations for a given day. Because different meteorological variables have different scales, the data needed first to be "centered," namely by subtracting the mean and dividing by the standard deviation – so that every variable will have mean zero and standard deviation one. The metric used in this analysis was uncentered correlation[2] (the other common metric being Euclidean distance).

The cluster analysis program was unable to handle the large number of days. Therefore, for analyses i), ii) and iii) stratified samples were taken, using 15 randomly selected days from each year, plus any days (8/3/90-8/6/90, 7/30/00-8/3/00, 9/18/00-9/19/00) of the key AUSPEX/SJVAQS and CCOS episodes that fell into one of the subsets.

[1] These are days identified by one of the three air districts – SJVAPCD, Sacramento APCD, and BAAQMD – as days that might be useful for photochemical modeling. These were interpreted as days with a 1-hour max ozone value at or exceeding: 145 ppb in SJV or 129 ppb in SV or 126 ppb in SFB.

[2] Symbolically, $\sum x_i y_i / \sqrt{\sum x_i^2 \sum y_i^2}$

Table 4-1. Comparisons of meteorological variables by cluster. For all and selected days exceeding the 8-hour ozone standard in Central California[ab]

Variable	Cluster Comparison	Cluster Medians: All 8-hour[a]			Cluster Comp. [c]	Cluster Medians: 8-hour but not 1-hour[b]	
		1	2	3		1n	2n
Max. temp. (°F)							
San Francisco	1<<<3, 1<<2, 2≈3	69	72	74	1<<<2	68	74
Sacramento	1<<<2<<<3	86	90	99	1<<<2	88	93
Stockton	1<2<<<3	88	90	98	1<<<2	88	94
Redding	2<1<<<3	95	92	102	1<<2	92	96
Fresno	2<1<<<3	95	92	100	1<2	93	95
Bakersfield	2<<<1<<<3	96	92	100	1≈2	93	94
Bethel Island	1<<<2<<<3	80.7	84.4	93.5	1<<<2	82.6	89.2
San Martin	1<<<2<<<3	79.9	85.2	94.0	1<<<2	81.6	90.7
Livermore	1<<<2<<<3	78.1	84.7	94.9	1<<<2	79.5	89.6
San Jose	1<<<2<<<3	79	83	88.5	1<<<2	78	87
850 mb 04 PST	2<<<1<<<3	67.6	62.6	72.8	1≈2	63.9	65.4
850 mb 16 PST	2<<<1<<<3	66.9	64.0	74.1	1<<2	64.8	66.9
fat – ave(fat)	1≈2<<<3	0.9	0.9	5.0	1<<2	-0.5	2.2
li – ave(li)	1<<<2<<<3	-6.0	2.2	10.2	1<<<2	-3.4	6.3
sac – ave(sac)	1<<<2<<<3	-4.9	1.9	7.7	1<<<2	-1.8	4.7
10 PST – 16 PST mean wind speed (mph)							
San Martin	1≈2≈3	8.5	8.6	8.2	2<1	9.1	8.3
Bethel Island	2≈3<<<1	15.6	10.7	10.6	2<<<1	14.6	8.9
Bakersfield	2<<<1≈3	8.7	7.9	9.1	1≈2	8.4	8.1
Sacramento	2≈3<<<1	9.6	6.7	6.4	2<<<1	8.2	6.3
San Francisco	1≈2≈3	14.1	13.6	14.4	2<<<1	15.3	12.9
Redding	2≈3<1	8.1	6.6	7.4	1≈2	7.6	7.1
Fresno	1≈2≈3	6.1	5.9	6.3	2<<1	6.3	5.7
Travis AFB	2≈3<<<1	17.7	9.9	10.1	2<<<1	14.8	7.6
Other variables							
04 PST inversion top	2<<3<<1	986	426	792	2<<1	895	440
04 PST inversion base	2≈3<<1	555	6	6	2<<<1	458	6
04 PST inv. strength	2<<<1<3	61.0	39.0	65.2	1≈2	57.0	53.4
Solar insolation	1≈2≈3	653	580	605	2<1	664	601
Pressure variables							
sfo 12 noon sea level	3<<1, 3<2, 1≈2	1015.2	1014.6	1013.4	2<<<1	1015.9	1013.5
rdd 12 noon sea level	1<<<2, 1≈3, 3<<2	1010.6	1012.2	1011.2	1≈2	1012.3	1011.8
bfl 12 noon sea level	1≈3<2	1011.2	1012.5	1010.8	2<1	1012.3	1011.3
sfo – rdd	2≈3<<<1	4.2	2.1	2.1	2<<<1	3.7	1.7
sfo – bfl	2≈3<<<1	3.6	2.4	2.5	2<<<1	3.5	2.0
rdd – bfl	1<<<2≈3	-0.3	0.5	0.2	2<<<1	-0.2	0.4
lag winds							
lag rdd 10-4 ws	1≈2≈3	6.5	6.0	5.9	1≈2	6.0	6.2
lag sac 10-4 ws	3<<<2<1	7.9	7.0	5.9	2<<<1	7.7	6.2
lag bi 10-4 ws	2<<1,3<<<1, 2≈3	11.3	9.0	8.2	2<<1	10.1	8.1
lag fat 10-4 ws	3<1≈2	6.7	6.8	6.0	2<<1	7.3	6.3
lag bfl 10-4 ws	2≈3,2<1, 3<<1	7.4	6.9	6.8	1≈2	7.1	7.0
lag temps							
lag sfo max temp	1≈2,1<<<3, 2<<3	70	71	75.5	1<<<2	69	73
lag (sfo – sac max t)	1<<<2,1≈3,3<<2	-20	-15	-21.5	1<2	-18	-17
lag 850 mb 16 PST temp	2<<<1<<3	68.7	61.9	72.3	1≈2	64.8	65.1

[a] Clusters using a stratified random sample of days with an exceedance of the federal 8-hour ozone standard (85 ppb) in at least one of the basins – SJV, SV or SFB. [b] Clusters using a stratified random sample of days with an exceedance of the federal 8-hour ozone standard (85 ppb) in at least one of the basins – SJV, SV or SFB *but not a 1-hour exceedance*. [c] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

4.1.2 Analysis of 8-hour Ozone Exceedance Days

Figure 4-1 shows the clusters for analysis i). A division was made resulting in 3 clusters, as shown. The following table compares the meteorological variables for these clusters, showing whether statistically significant differences exist, based on pairwise Mann-Whitney tests[3].

From Table 4-1, Cluster 3 has higher surface temperatures everywhere in Central California (CC) except San Francisco, higher 850 mb 04 PST and 16 PST temperatures and higher previous-day temperatures at SFO and 16 PST 850 mb. Cluster 1 has the lowest Bay Area / Sacramento temperatures, but Cluster 2 has the lowest San Joaquin and elevated temperatures. Cluster 1 shows stronger SFO – valley pressure gradients and stronger winds through the Carquinez Straight. Cluster 2 has the weaker inversions than the others; Cluster 1 has higher inversion base and height than the others.

Cluster 3 seems to capture many of the more stagnant days with high temperatures throughout CC and little transport. Cluster 1 days appear to be ones with strong transport, with the relatively coolest Bay Area and Sacramento temperatures (in fact, below average), but reasonably hot in Fresno and Bakersfield. Cluster 2 days are cool in the SJV and aloft, not hot in the SFB/SV, and are without strong transport.

Comparison with principal components

With 42 variables, it is hard to visualize how the clusters differ. Clusters represent groupings that are separated in space, by some metric. Thus, the first few principle components – which represent the majority of the variation of the data – may provide a method.

Table 4-2 shows the correlations between the cluster means and the first 8 principal components identified as pc1, pc2.....,pc8. Note that the strongest correlations are with the first two principal components, suggesting that these may be sufficient for presenting the data. **Figure 4-2** shows the cluster days projected onto the first two components. The clusters are reasonably well differentiated, with the cluster positions related to the correlations in Table 4-2. Specifically, Cluster 1 is concentrated in the upper left-hand quadrant – i.e., low on component 1 and high on component 2. Cluster 2 is concentrated in the lower half of the figure, generally to the left (low on component 1 and somewhat low on component 2). Cluster 3 is concentrated above a diagonal line through the origin from the upper left to lower left – containing all the highest days for component 1 and generally higher for component 2.

[3] The Mann-Whitney test is a nonparametric test for the difference in the median between two populations. It was used instead of the t-test because it is robust for data that are highly skewed, bimodal, long-tailed, or otherwise very different from the Gaussian distribution. It can be shown to have good power relative to the t-test for ANY statistical distribution.

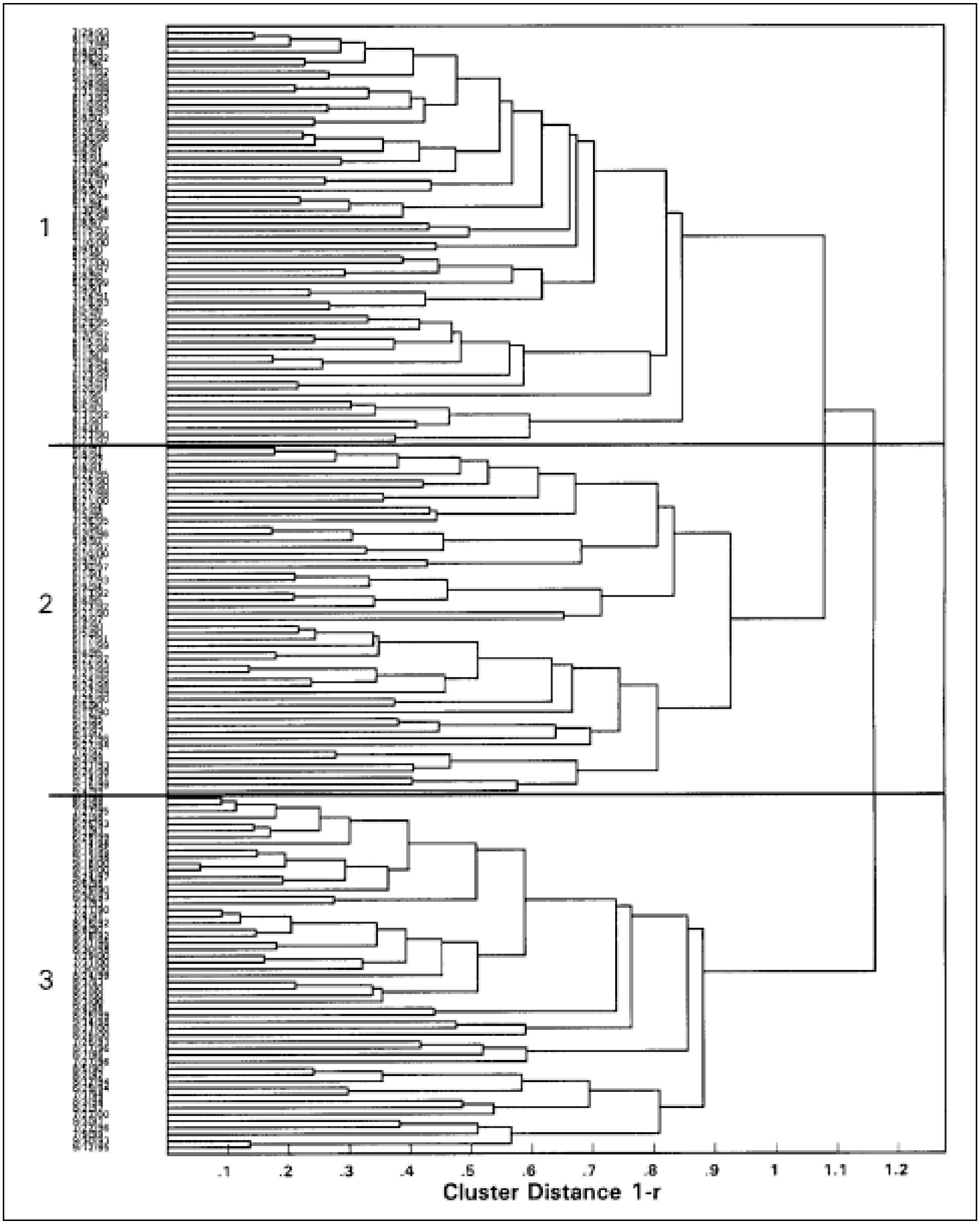


Figure 4-1. Cluster of 8-hour ozone exceedance days during 1990 to 2000, using 42 centered meteorological variables. Clustering used uncentered correlation as the distance metric. Horizontal lines show divisions between clusters.

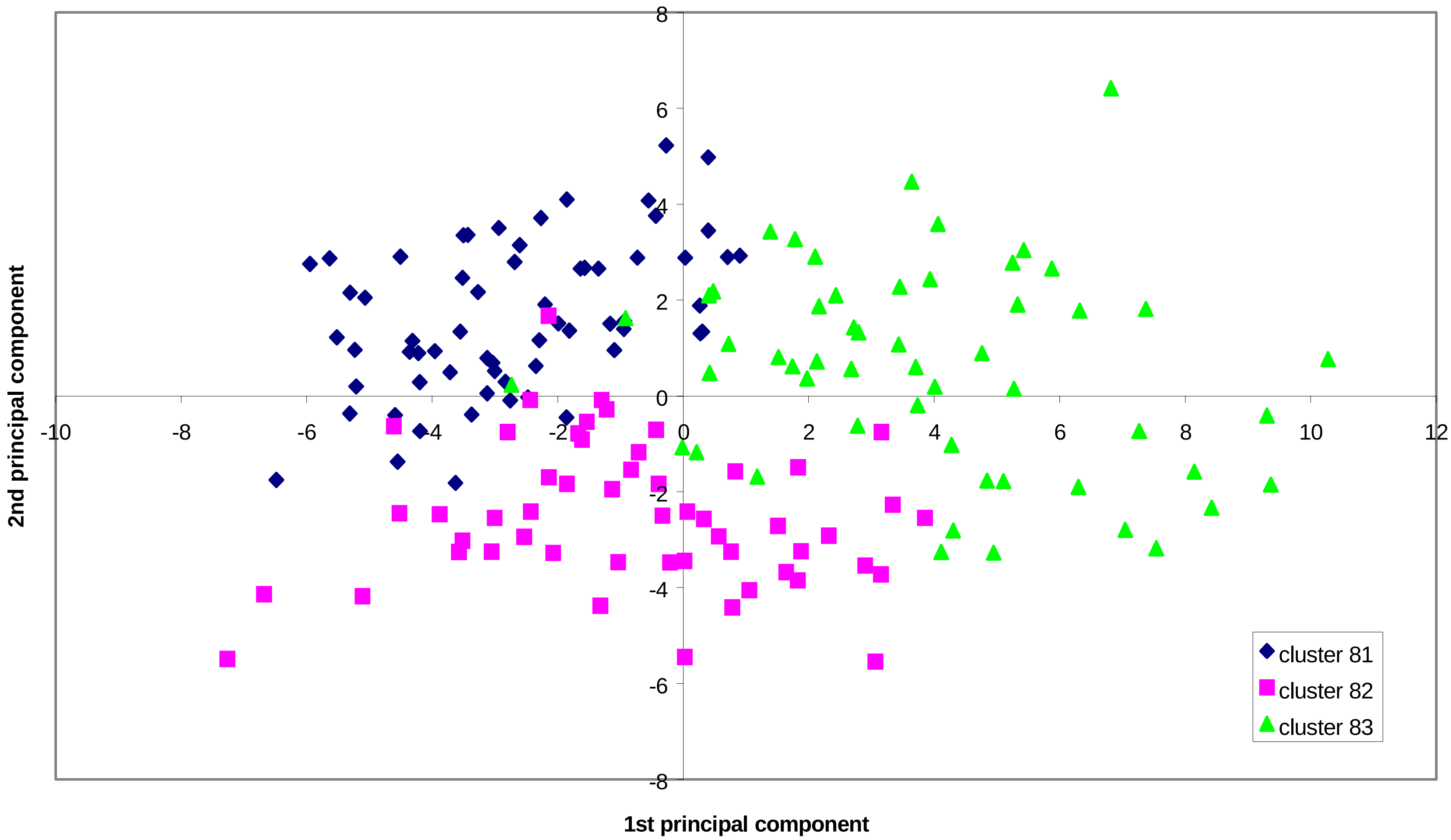


Figure 4-2. 8-hour clusters projected on the 1st two principal components of the 42 meteorological variables. 1st component represents warm days, especially in the Bay Area and Sacramento, and light winds through the Sacramento Delta. The second component represents a strong pressure gradient between SFO and the valley and previous-day sf-sac temperature gradient, but also high Bakersfield and Fresno max and 850 mb 04 PST temperatures, and previous-day high 850 mb 16 PST temperatures.

Table 4-2. Correlations between cluster means and first eight principal components

Cluster:	pc1	pc2	pc3	pc4	pc5	pc6	pc7	pc8
1	-.85	.57	.18	.07	.18	-.03	-.03	-.02
2	-.16	-.89	-.26	.44	-.07	-.11	.05	.04
3	.98	-.01	-.02	-.35	-.14	.10	-.00	-.01

As discussed in the figure caption, pc1 is associated with warm temperatures in the Bay Area/Sacramento and light winds through the Carquinez Strait. Pc2 is more complex, corresponding to stronger pressure gradient between SFO and the valley, but also higher Fresno, Bakersfield and 850 mb 04 PST. temperatures, high previous-day 850 mb 16 PST. temperature, and weak previous-day sf-sac temperature gradient.

Comparison of air basin ozone by cluster

The primary objective of this analysis is to find out the extent to which these meteorological clusters might represent distinct regimes for high ozone. One obvious question is the extent that high ozone occurs in the different clusters. **Table 4-3** shows Mann-Whitney test results for 8-hour and 1-hour ozone for the 3 clusters.

Table 4-3. Comparison of basin 8-hour and 1-hour ozone medians (ppb) by cluster

	8-hour Ozone				1-hour Ozone			
	Clust. Comparison[a]	Cluster Medians 1	2	3	Clust. Comparison[a]	Cluster Medians 1	2	3
SJV	1≈2<<<3	94	94	105.5	1≈2<<<3	112	109	127.5
SV	1≈2<<<3	78	75	92	1≈2<<<3	90	85	110
SFB	1<<<2<<3	42	54	70	1<<<2<<3	54	70	90.5

[a] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

For every basin, Cluster 3 has higher median ozone than either Cluster 1 or 2. For SJV and SV, there is no statistical difference in the ozone levels for Clusters 1 and 2, but for SFB, Cluster 1 days have much lower ozone.

Table 4-4 shows numbers of exceedances of the 8-hour and 1-hour standards for the 3 clusters. The table shows that Cluster 3 has higher potential for 1-hour exceedances in all the air basins, especially in the SFB and higher potential for 8-hour exceedances in SV and SFB. (Almost all days are 8-hour exceedance days for SJV.)

Table 4-4. 8-hour and 1-hour exceedance days by cluster

	8-hour Exceedances by Cluster			1-hour Exceedances by Cluster		
	1	**2**	**3**	**1**	**2**	**3**
SJV	61	49	53	15	10	32
SV	19	14	38	4	1	14
SFB	0	3	16	0	0	8
Total Days in cluster	63	53	54	63	53	54

There may be marginally greater potential for exceedances in Cluster 1 than Cluster 2, but the differences appear of little practical importance.

Figure 4-3 shows the 8-hour ozone levels of one basin relative to another. In particular, the vertical axis represents the ratio of Sacramento to SFB 8-hour ozone, and the horizontal axis represents the ratio of SJV to the root mean square of SV and SFB. There is a weak pattern where Cluster 1 values lie mostly in the upper right of the plot, indicating that SFB is low relative to SV and SJV for Cluster 1. But, mainly the clusters do not differentiate the basins well.

4.1.3 Analysis Of Days with 8-hour Ozone Exceedances but Not 1-hour

Cluster analysis was performed restricted to the 441 days in the group with 8-hour but not 1-hour exceedances. A stratified random sample of 166 days was taken and a cluster analysis performed. Two distinct clusters emerged.

The last two columns of Table 4-1 show a comparison of the meteorological variables for these clusters. To distinguish from the previous analysis, these clusters will be referred to 1n and 2n. From the table, Cluster 2n was warmer, had lighter winds, and lower pressure gradients than Cluster 1n. Cluster 1n resembles Cluster 1, while Cluster 2n shows some of the aspects of Cluster 3, though with lower temperatures.

Table 4-5 shows correlations of the clusters with the first 8 principal components. As with the previous analysis, the strongest correlations are with the first 2 components, pc1 and pc2.

Table 4-5. Correlations between cluster means and first 8 principal components

Cluster:	pc1	pc2	pc3	pc4	pc5	pc6	pc7	pc8
1n	-.99	.14	-.12	.19	.14	-.06	.15	-.02
2n	.70	-.75	.14	.18	-.05	.06	-.01	-.04

Figure 4-4 shows the cluster days projected on the first two principal components. Unlike Figure 4-2, there is substantial overlap between the clusters. However, Cluster 1 days tend to be higher on the second principal component than Cluster 2 days. One clear-cut feature is that neither cluster is high on component 1.

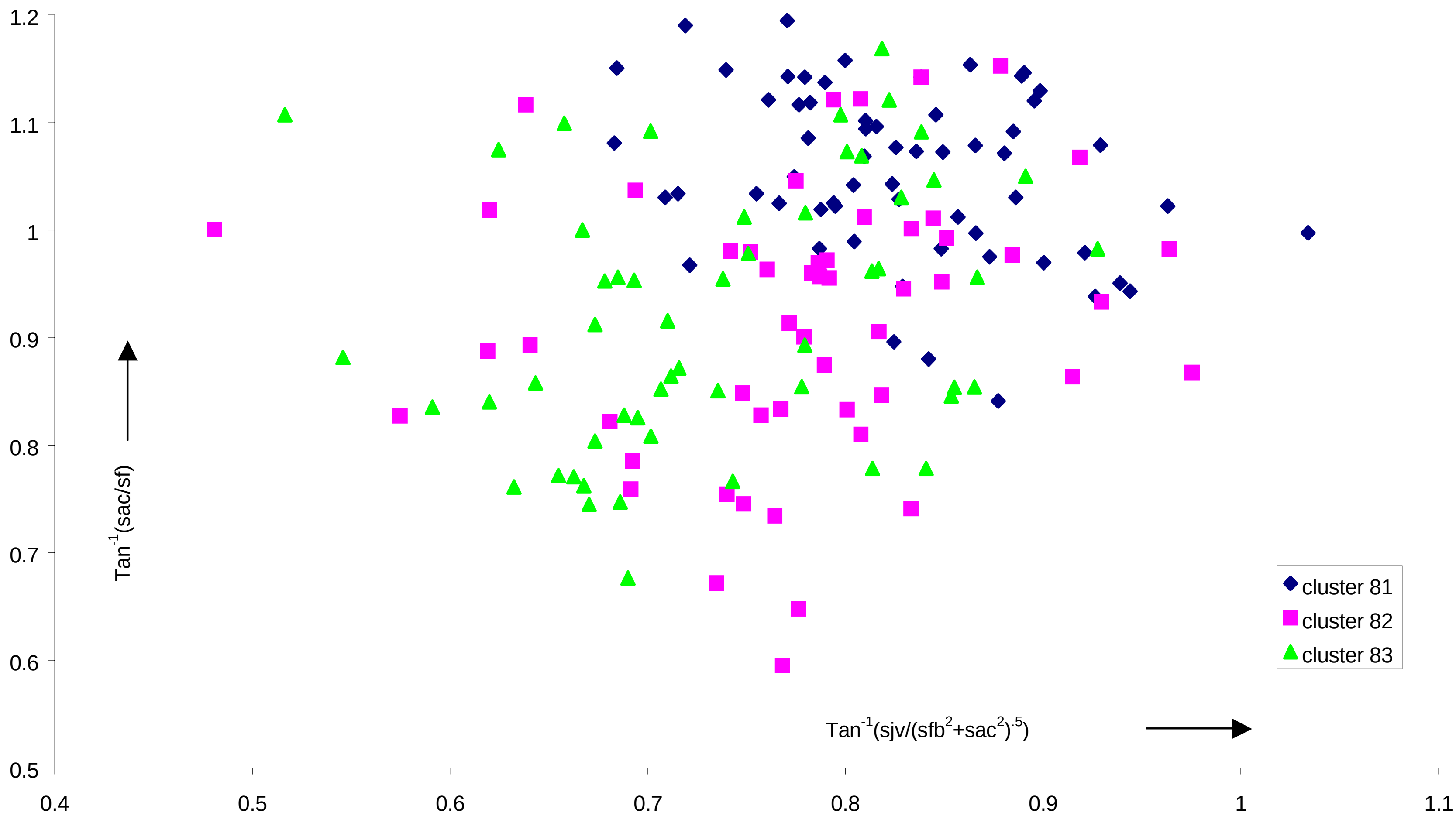


Figure 4-3. Meteorological clusters and 3-basin daily max. 8-hour ozone. Randomly selected days 1990 to 2000 with a federal 8-hour ozone exceedance in sjv, sv or sfb air basins plotted to show relative severity. Green, red and purple represent the three met. based clusters using all 42 met variables. There are 170 points total, about one-fourth the number of federal 8-hour exceedance days in 1990 to 2000.

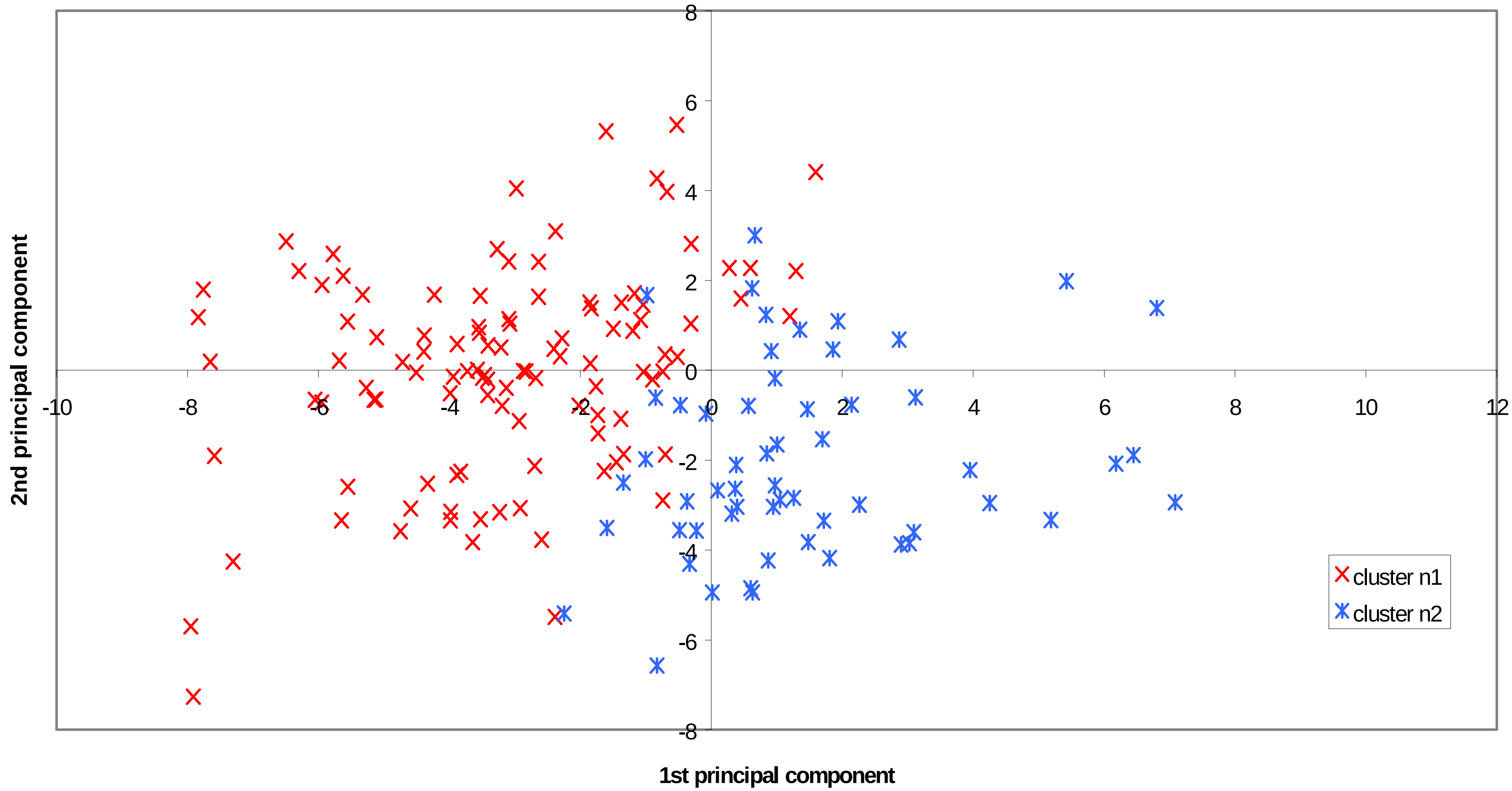


Figure 4-4. Clusters for 8-hour days without 1-hour ozone exceedances, projected on the 1st two principle components of the 42 meteorological variables. 1st component represents warm days, esp. in the Bay Area and Sacramento, and light winds through the Sacramento Delta. The second component represents a strong pressure gradient between SFO and the valley and previous-day sf-sac temperature gradient, but also high Bakersfield and Fresno max and 850 mb 04 PST temperatures, and previous-day high 850 mb 16 PST temperatures.

Comparison of air basin ozone by cluster

Table 4-6 presents cluster medians and pairwise comparisons by basins. **Table 4-7** presents a comparison of the numbers of exceedances of the federal ozone standards by cluster and basin. There was no statistical difference between the clusters for SJV or SV. Almost all days in either cluster were 8-hour exceedance days for SJV. The majority of days in each cluster were 8-hour exceedance days for SV, but the percentage of days was a bit higher for Cluster n2 – 70% (40 out of 57) compared with 56% (61 out of 109) for Cluster n1. For the Bay Area, the differences were more dramatic: only 4% (4 out of 109) of Cluster n1 days exceeded the 8-hour standard, compared with 44% (25 out of 57) of the Cluster n2 days. The differences in the cluster medians was highly statistically significant. Of course, by definition, there were no days exceeding the 1-hour Federal Standard.

Table 4-6. Comparison of basin 8-hour and 1-hour ozone medians (ppb) by 8- not 1-hour cluster

	8-hour Ozone			**1-hour Ozone**		
	Cluster Comparison[a]	**Cluster Medians**		**Cluster Comparison[a]**	**Cluster Medians**	
		n1	**n2**		**n1**	**n2**
SJV	1≈2	92	94	1≈2	110	110
SV	1≈2	76	81	1≈2	87	91
SFB	1<<<2	46	62	1<<<2	60	80

[a] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

Table 4-7. 8-hour and 1-hour exceedance days by cluster

	8-hour Exceedances by Cluster		**1-hour Exceedances by Cluster**	
	1n	**2n**	**1n**	**2n**
SJV	105	57	0	0
SV	61	40	0	0
SFB	4	25	0	0
Total Days in cluster	109	57	0	0

4.1.4 Analysis of Days with 1-hour Ozone Exceedances

Interestingly, every federal 1-hour exceedance day was also an 8-hour exceedance day. Specifically, there were 404 1-hour exceedance days, all of which had exceedances of the 8-hour standard. Of these, 322 contained complete data for the 42 meteorological variables.

As with the 8-hour data, a random sample was selected – 15 days for each year, except for 1997 where all 13 1-hour exceedance days were used. Also included were all AUSPEX/SJVAQS and CCOS days (8/3-6/00, 7/30/00-8/3/00 and 9/18/00-9/19/00) with federal exceedances. The data were centered. A cluster analysis was performed, and the three main clusters identified.

Table 4-8 lists the cluster medians for each meteorological variable and results of pairwise Mann-Whitney tests. To distinguish from the earlier clusters, these clusters are denoted 11, 12 and 13.

Cluster 12 is similar to Cluster 81, with the lowest temperatures, highest Carquinez Strait mid-day winds, and the strongest pressure gradients between San Francisco Airport (SFO) and the Central Valley. Cluster 11 has the highest temperatures, similar to Cluster 83. It also has similar SFO-Valley pressure gradients and mid-day Carquinez Strait wind velocities.

Figure 4-5 shows the projection of these clusters on the first two principal components. Cluster 11 is almost entirely positive on both axes. Cluster 12 is the most negative of the three on principal component 1. Cluster 13 is positive on the 1^{st} component and negative on the 2^{nd}.

4.1.5 Analyses of Episode Days

Cluster analysis was also performed restricted to episode days. Two clusters were selected. Table 4-8 shows comparisons by meteorological variable. The differences in the two clusters are almost entirely that Cluster e1 had higher temperatures than Cluster e2. **Figure 4-6** shows the projections. Cluster e1 lies almost entirely to the right of Cluster e2 on the component 1 axis. Their relationship is similar to that of Cluster 11 to Cluster 12 in Figure 4-5.

Comparison of air basin ozone by cluster

Table 4-9 shows medians and pairwise Mann-Whitney test results for the clusters by basin. **Table 4-10** shows exceedance counts for the three clusters.

For SJV, almost every day exceeds both the 8-hour and 1-hour standards. However, half of the episodes occurred in Cluster 11 though a number occurred in the other clusters. The median 1-hour ozone was substantially lower for Cluster 12 than the others. For SV, again there was not much to choose for 8-hour exceedances, although the 8-hour medians were highest for Cluster 11. For 1-hour exceedances and episode days, however, SV experienced the majority on Cluster 11 days, which were, not surprisingly, those with highest SV median 1-hour ozone. For SFB, Cluster 12 did not even have an 8-hour exceedance; the other two clusters were indistinguishable in producing high ozone.

Table 4-8. Comparisons of meteorological variables by cluster – for clusters based on met variables –for <u>all</u> and selected days exceeding the 1-hour ozone standard in Central California[ab]

Variable	Cluster Comparison	Cluster Medians: ALL 1-hour[a]			Cluster Comp. [c]	Cluster Medians: 8-hour but not 1-hour[b]	
		11	12	13		e1	e2
Max. temp. (°F)							
San Francisco	2<<<1≈3	74	70	77	2<<<1	77	71
Sacramento	2<<<3<<<1	102	91	97	2<<<1	102	95
Stockton	2<<<3<<<1	101	92	97	2<<<1	102	96
Redding	2<3<<<1	104	97	99.5	2<<<1	105	102
Fresno	2≈3<<<1	103	98	98	2<<<1	104	99
Bakersfield	2≈3<<<1	102	98	97	2<<<1	103	99
Bethel Island	2<<<1≈3	95.3	83.9	93.3	2<<<1	97.3	89.1
San Martin	2<<<1≈3	95.9	83.6	95.0	2<<<1	97.4	90.8
Livermore	2<<<3<<1	97.4	83.6	94.4	2<<<1	99.5	91.4
San Jose	2<<<1≈3	91	80.5	89.0	2<<<1	94	84
850 mb 04 PST	2≈3<<<1	75.2	70.4	69.3	2<<<1	77	71.7
850 mb 16 PST	2≈3<<<1	75.2	70.2	70.7	2<<<1	77	72.3
fat – ave(fat)	1≈3, 2≈3, 2<<<1	7.7	3.5	5.6	2<<<1	8.9	5.4
li – ave(li)	2<<<1≈3	13.0	0.2	11.3	2<<<1	14.6	7.5
sac – ave(sac)	2<<<3<1	9.8	0.8	8.0	2<<<1	11.2	5.7
10 PST – 16 PST mean wind speed (mph)							
San Martin	3<<1≈2	9.8	9.8	7.7	1≈2	9.1	8.9
Bethel Island	3<<<1<<<2	10.6	14.8	6.7	1<2	9.0	11.0
Bakersfield	2≈3<1	9.1	8.7	8.4	2<<1	9.1	8.0
Sacramento	1≈3<<<2	6.4	8.1	5.5	1≈2	6.0	6.1
San Francisco	3<<1≈2	14.1	15.3	11.7	1≈2	13.1	14.1
Redding	2≈3≈1	6.5	7.2	6.7	1≈2	6.9	6.8
Fresno	3<<1≈2	6.5	6.4	5.5	1≈2	6.0	6.0
Travis AFB	3<<<1<<<2	9.3	15.2	6.3	1<2	7.7	10.4
Other variables							
04 PST inversion top	1≈2, 3<1, 3<<<2	769	850	583.5	1<2	690	791
04 PST inversion base	1≈3<<<2	6	386.5	6	1<<2	6	215
04 PST inv. strength	2≈3<<1	68.5	62.6	61.4	1≈2	65.7	65.8
Solar insolation	1≈2, 3<1, 3<2	631	616.5	558.5	1<2	563	608
Pressure variables							
sfo 12 noon sea level	3<1<2, 3<<<2	1013.5	1015.2	1012.5	1<<<2	1012.5	1014.9
rdd 12 noon sea level	1≈2≈3	1011.2	1011.2	1011.3	1<2	1010.7	1011.8
bfl 12 noon sea level	1≈2≈3	1010.9	1011.2	1010.5	1<<2	1009.9	1011.6
sfo – rdd	3<<<1<<<2	2.4	3.5	1.2	1<<2	2.2	2.8
sfo – bfl	3<<<1<<<2	2.6	3.8	1.8	1<<2	2.6	3.1
rdd – bfl	1≈2, 1<<3, 2<3	0.2	0.3	0.7	1≈2	0.5	0.2
lag winds							
lag rdd 10-4 ws	1≈2, 2≈3, 1<3	5.6	6.1	6.7	1≈2	6.1	5.8
lag sac 10-4 ws	1≈3, 2≈3, 1<<<2	5.4	6.6	5.8	1≈2	5.5	6.0
lag bi 10-4 ws	1<2, 3<<1, 3<<<2	8.6	9.5	7.0	1≈2	8.0	9.2
lag fat 10-4 ws	3<1≈2	6.3	6.2	5.8	1≈2	5.8	6.0
lag bfl 10-4 ws	1≈2, 1≈3, 3<2	6.9	6.9	6.6	2<1	7.3	6.7
lag temps							
lag sfo max temp	2<1, 1<3, 2<<<3	74	71	80	2<<<1	80	72
lag (sfo – sac max t)	1<2<<<3	-25	-21	-13	1≈2	-21	-23
lag 850 mb 16 PST temp	3<<<2<1	74.5	70.7	68.3	2<<<1	75.6	72.0

[a] Clusters using a stratified random sample of days with an exceedance of the federal 8-hour ozone standard (85 ppb) in at least one of the basins – SJV, SV or SFB. [b] Clusters using a stratified random sample of days with an exceedance of the federal 8-hour ozone standard (85 ppb) in at least one of the basins – SJV, SV or SFB *but not a 1-hour exceedance*. [c] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

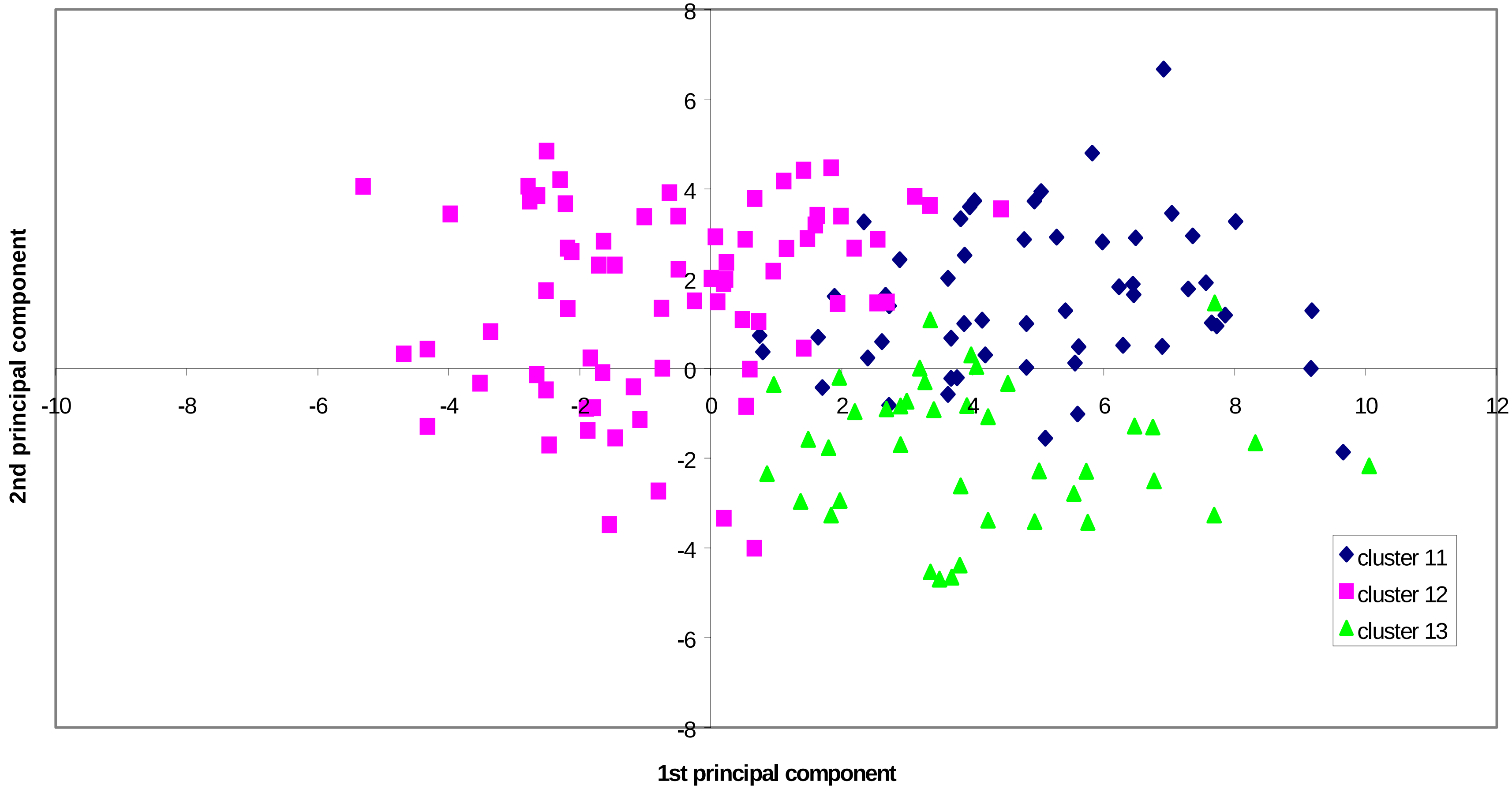


Figure 4-5. Clusters for 1-hour exceedance days, projected on the 1st two principal components of the 42 meteorological variables. 1st component represents warm days, especially in the Bay Area and Sacramento, and light winds through the Sacramento Delta. The second component represents a strong pressure gradient between coast and the valley and previous-day sf-sac temperature gradient, but also high Bakersfield and Fresno max and 850 mb 04 PST temperatures, and previous-day high 850 mb 16 PST temperatures.

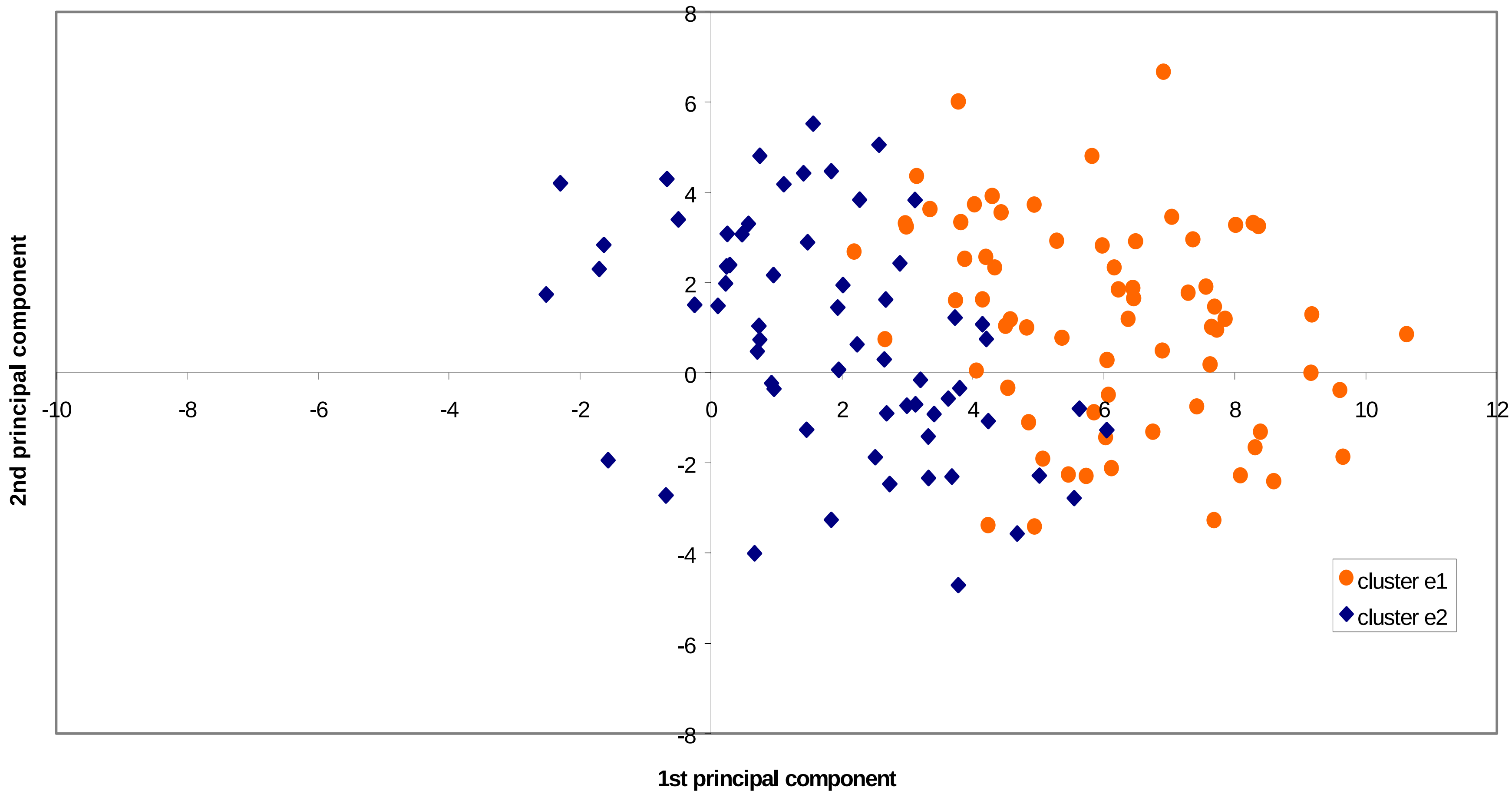


Figure 4-6. Clusters for 1-hour episode days, projected on the 1st two principal components of the 42 meteorological variables

Table 4-9. Comparison of basin 8-hour and 1-hour ozone by 1-hour cluster

	8-hour ozone				1-hour ozone			
	Clust. Comparison[a]	Cluster Medians			Cluster Comparison[a]	Cluster Medians		
		11	12	13		11	12	13
SJV	2<1, 1≈3, 2≈3	110	107	109	2<<<1≈3	140	130.5	139
SV	2<<<1, 3<<1, 2≈3	99	84.5	90	2≈3, 2<<<1, 3<<1	120	98	108.5
SFB	2<<<1≈3	76	50	77	2<<<1≈3	100	65.5	99.5

[a] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

Table 4-10. 8-hour and 1-hour exceedance and episode days by cluster

	8-Hour Exceedances By Cluster			1-Hour Exceedances By Cluster			Episode Days By Cluster		
	11	12	13	11	12	13	11	12	13
SJV	55	72	40	52	66	39	17	8	9
SV	44	36	26	22	16	4	20	14	2
SFB	18	0	12	9	0	7	9	0	7
Total Days in cluster	55	72	40	55	72	40	55	72	40

[a] Results of pairwise Mann-Whitney tests.

Tables 4-11 and 4-12 show ozone comparisons for the two episode day clusters. For SJV and SV, the clusters are similar, with little or no statistical difference in the median ozone. For SFB, however, the differences are dramatic, with highly significant differences in the medians and the large majority of its exceedances and episode days falling into Cluster e1.

Table 4-11. Comparison of basin 8-hour and 1-hour ozone by episode day cluster

	8-hour ozone			1-hour ozone		
	Cluster Comparison[a]	Cluster Medians		Cluster Comparison[a]	Cluster Medians	
		e1	e2		e1	e2
SJV	2<1	117	112	1≈2	147	145
SV	1≈2	106	99	2<1	130	128
SFB	2<<<1	82	65	2<<<1	114	87

[a] Symbols: ≈ not statistically significant, < significant at 0.05, << significant at 0.005, <<< significant at 0.0001, based on Mann-Whitney tests of each pair of clusters (1 vs. 2, 1 vs. 3 and 2 vs. 3).

Table 4-12. 8-hour and 1-hour exceedance and episode days for episode clusters

	8-hour Exceedances by Cluster		**1-hour Exceedances by Cluster**		**Episode Days by Cluster**	
	e1	**e2**	**e1**	**e2**	**e1**	**e2**
SJV	69	62	65	50	40	34
SV	59	53	40	32	37	31
SFB	34	7	26	5	26	5
Total Days in cluster	69	62	69	62	69	62

4.1.6 Comparisons of the Various Clusters

A simple comparison of the four cluster analyses is to plot their means on the first two principal components as shown in **Figure 4-7**. One pattern that emerges is three pairs of clusters e1/e2, 11/12 and 83/81 with the first of the pair roughly to the right of the second, i.e similar on component 2, but different on component 1. The righthand member always has higher median ozone, and except for some episode day comparisons, significantly higher.

Cluster 13 days are high on component 1 but low on component 2. This indicates high Bay Area temperatures and low transport, but lower Valley and 850 mb temperatures. Cluster 82 was low on both components and had relatively low ozone in all three air basins.

4.1.7 Relationship to AUSPEX/SJVAQS and CCOS Days

Table 4-13 shows what field study days fell into what clusters. In every case, 8/3/90 and 8/4/90 fall into the cluster that is lower on pc1 whereas 8/5/90, 8/1/00, and 8/2/00 fall into the higher pc1 cluster. Of special interest is that 9/18/00 and 9/19/00 fall into cluster 13, suggesting this may have been a period with substantially different meteorology from the other two episode periods (8/3/90-8/5/90 and 7/30/00-8/2/00).

Table 4-13. Clusters in which AUSPEX/SJVAQS and CCOS days occurred

	AUSPEX/SJVAQS			**CCOS**						
	8/3/90	**8/4/90**	**8/5/90**	**7/30/00**	**7/31/00**	**8/1/00**	**8/2/00**	**8/3/00**	**9/18/00**	**9/19/00**
8-hr Cluster	81	81	83	83	83	83	83	83	83	83
1-hr Cluster	12	12	11	11	11	11	11	12	13	13
Epi Cluster	e2	e2	e1	NA	NA	e1	e1	NA	e1	e1

4.1.8 Summary

Although not totally reproducible, the cluster analyses found some consistent patterns. In every case, there were high correlations between cluster means and at least one of the first two principal components of the centered 8-hour data; plots of the clusters projected onto these components show reasonably good separation. In other words, even though the data are

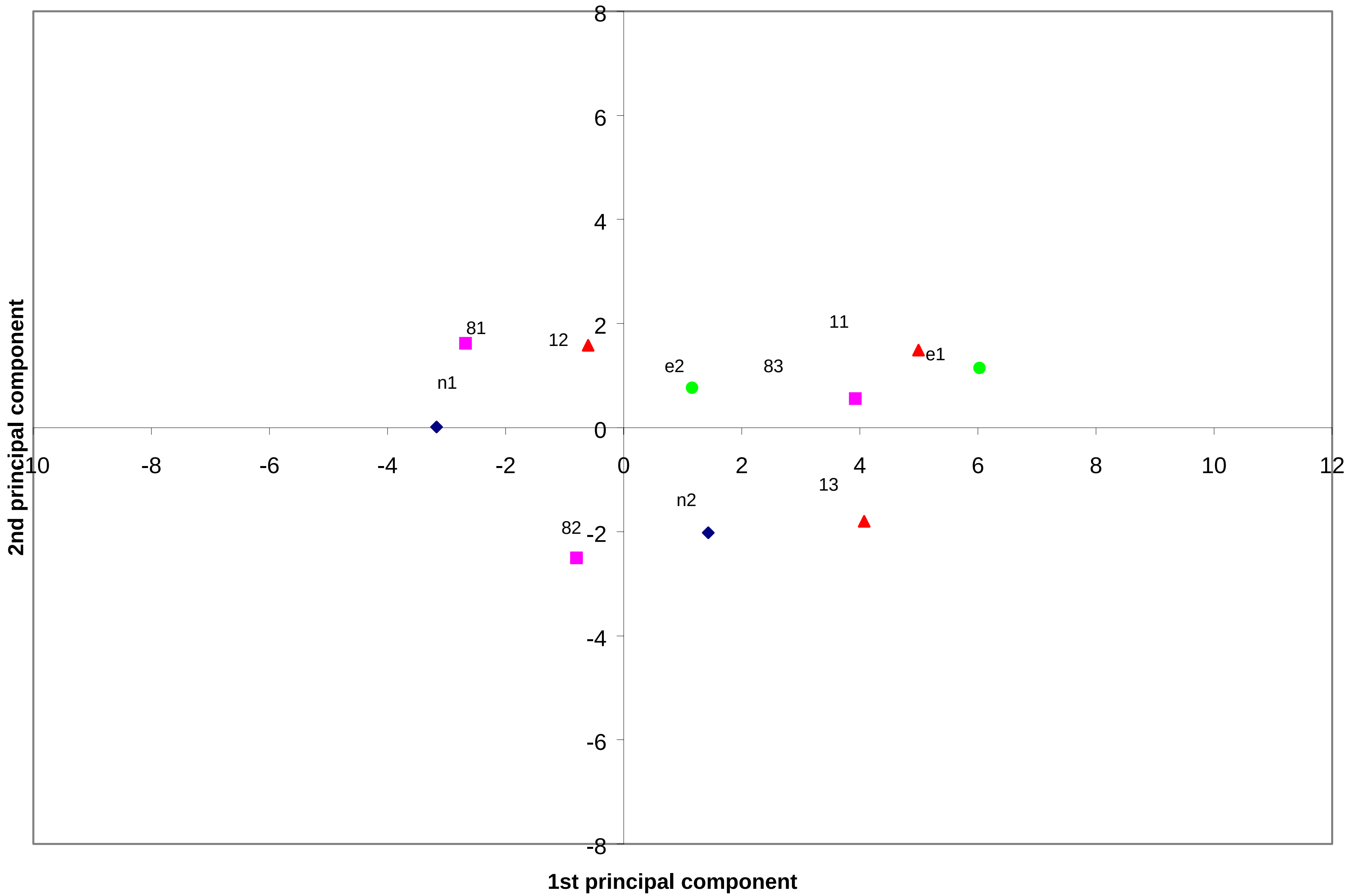


Figure 4-7. Cluster means projected on 1st two principal components

42-dimensional, the first 2 principal component dimensions are, to a great extent, able to reproduce those distinctions.

In every analysis, at least two clusters showed large differences on the first principal component. This component represents high surface temperatures, especially in the Bay Area, weak SFBay-Valley pressure gradients, and only light winds through the Carquinez Strait. The second component represents a strong SFBay-Valley pressure gradients and prior-day San Francisco-Sacramento temperature gradient, higher Bakersfield and Fresno maximum surface temperatures, 04 PST 850 mb temperatures, and prior-day 16 PST. temperatures.

One finding of these analyses was that the meteorological clusters often represented groups of days with substantially different ozone. Considering the pairs of clusters that differed on pc1 but were essentially equal on pc 2 (83/81, 11/12, and e1/e2), the ozone in the cluster with the higher pc1 values was higher on average. Of course, to some extent, this is equivalent to saying that pc1 represented hotter as opposed to cooler days and that ozone is higher on hotter days.

A second finding might be of more interest, namely the second component, pc2 with the 1-hour clusters. Sacramento ozone was considerably higher in Cluster 11 than Cluster 13, even though these had similar values of pc1. Cluster 11 had higher temperatures, but Cluster 13 had lower pressure gradients and winds through the Carquinez Strait. Also note that both of these clusters produce ozone episodes in the Bay Area and SJV.

The 1-hour cluster analysis put the AUSPEX/SJVAQS and CCOS episode days into different clusters, suggesting that the 9/18/00-9/19/00 cluster had qualitatively different meteorology from the 8/3/90-8/5/90 and 7/30/00-8/3/00 episodes. This is in agreement with the descriptive analyses discussed in Section 3.

In should be noted that these variables do not congregate in two distinct clouds; in no case were there two clusters that were both internally homogeneous and also radically different. Rather, the meteorological data constitute a continuum. Nevertheless, the meteorology and relative ozone levels at the ends of the continuum do appear to be qualitatively, not just quantitatively, different.

4.1.9 A Note About Cluster Analysis

Cluster analysis is hardly an exact science. Rather it is another tool for exploring data – seeking to find distinct clouds of points in high dimensional space. The reality, however, is that in our case as in many others, genuinely distinct clouds do not exist. Rather, the cluster analysis will make a somewhat arbitrary dividing line (region actually) between sections of the data. The number of clusters chosen in this investigation is arbitrary. There are statistical tests available but they weren't used here.

A second problem is choice of data and centering. Depending on which variables are chosen and how they are centered/scaled, the relative importance of various factors will change. The meteorological data I'm using has quite a few temperature variables. This may account for temperature's predominance as a key division point between clusters. If we center/scale all the data, then restrict the analysis to high ozone (i.e., high temperature) days, we get somewhat different answers than if we first restrict the data, then do the center/scaling.

Nevertheless, the clusters shown below do represent distinct sections of the data, based on some metric and seem to show patterns that make some sense. Perhaps the best interpretation is that there aren't two or three totally distinct sets of conditions that produce high ozone, but rather a continuum of conditions from less to greater transport and varying ozone potential in different places. The clusters shown represent different portions of this continuum.

4.2 Winds Aloft Statistics

In this section, large-scale or synoptic wind fields are examined to determine whether significant differences from year to year can be readily identified. Winds aloft measured at Oakland by the National Weather Service twice-daily balloon-soundings (rawinsondes) are utilized. The winds at the 500 mb pressure surface (about 5.9 km above sea level) were analyzed. Broad synoptic scale patterns are usually discernable at the 500 mb level because it is above possible influences from regional terrain (i.e. the Sierra Nevada and Coast ranges) and is a standard level reported by the NWS on all soundings. A single parameter, single station analysis such as this can provide indications of the relative positions of major troughs and ridges. Southwest winds at 500 mb are indicative of ridging to the east of Oakland over the Great Basin and troughing to the west over the eastern Pacific. Conversely, northwest winds aloft are often associated with an approaching ridge to the west of California and troughing to the east over the Great Basin or Inter-Mountain area. Light west-northwest to west-southwest winds typically occur when pressure gradients are weakest, such as near the center of a ridge, or in a large flat high pressure area.

The Oakland twice-daily 500 mb winds, measured during the primary ozone season (June-September), were sorted into directional categories for each of the 16 points of the compass. Wind speeds within each directional category were grouped and the frequency of occurrence within each direction and velocity group determined. The results are used to construct so-called wind rose diagrams as shown in **Figure 4-8**. In this figure, overall statistics for the 15-year period are shown. Wind roses for each of the individual years are given in Appendix C of this report. In the figures, there is a bar for each 22.5 degree arc of the compass, its length proportional to the frequency of occurrence. Each direction bar is segmented by the wind speed frequency of occurrence in percent. As can be seen from Figure 4-8, the prevailing wind directions for the 15 year data base were from the southwest quadrant. This is in agreement with the climatological description in Section 2 that states that the prevailing 500 mb synoptic pattern during CCOS 2000 was ridging to the east of California, and frequent troughing to the west.

Year-to-year differences in the wind frequency distributions are summarized in **Table 4-14**. In this table, the prevailing and secondary wind directions are given. In those instances where the frequency of occurrence in two direction categories are equal, both are shown. The prevailing winds for the 15 year period inclusive are also shown in the last row of the table. The years1990 and 2000 are of special interest as AUSPEX/SJVAQS and CCOS were conducted during those periods. The wind frequency distribution in 1990 was similar to the 15 year period whereas in 2000 the winds tended to have a more southerly component. The more southerly tendency is indicative of greater frequency of troughing off the California coast. Wind rose diagrams for the two years are shown in **Figures 4-9 and 4-10**. The average wind speed at 500 mb in 2000 was one of the lowest of the period of record (only 1987 and 1998 averages were less). The 1990 wind speeds were 2 m/s or 40 percent greater on the average than those measured in 2000.

Based solely on wind frequency of occurrence, 1998 was the most comparable year of the 15-year data set to 2000, both in prevailing directions and average speeds.

Table 4-14. Prevailing Wind Direction at 500 mb

	Primary		Secondary	
Year	Wind Direction	Frequency	Wind Direction	Frequency
86	WSW	21.9%	W	19.2%
87	SSW	16.2%	W, SE	12.4%
88	SW	26.0%	W, WNW	14.0%
89	NW	16.1%	SSW	14.2%
90	W, WSW	18.5%	SW	15.4%
91	WSW	16.7%	WNW	15.3%
92	W, SW	16.5%	SSW	15.2%
93	WSW	29.9%	W	14.9%
94	WSW	19.0%	SSW, SE	14.3%
95	W, NW	19.4%	WNW, SSW	12.9%
96	WSW	24.5%	SSW	22.4%
97	SW	35.7%	W, SSW	14.3%
98	WSW	18.6%	SW	14.5%
99	WSW	11.6%	W	11.2%
00	SW	24.8%	WSW	12.1%
Total Avg.	WSW	14.2%	SW	14.1%

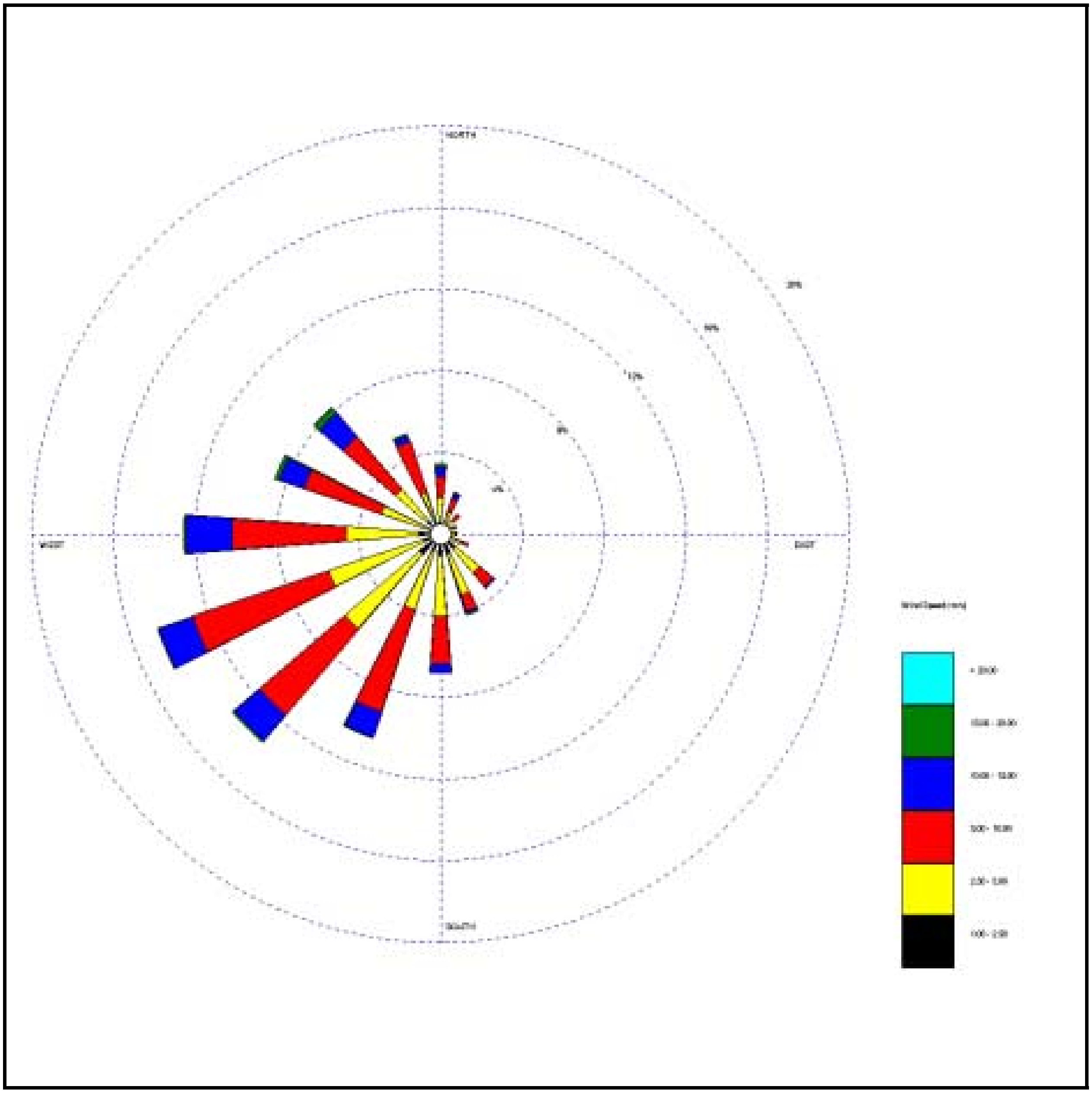


Figure 4-8. Wind rose frequency diagram for Oakland 500 mb winds for June to September 1986-2000

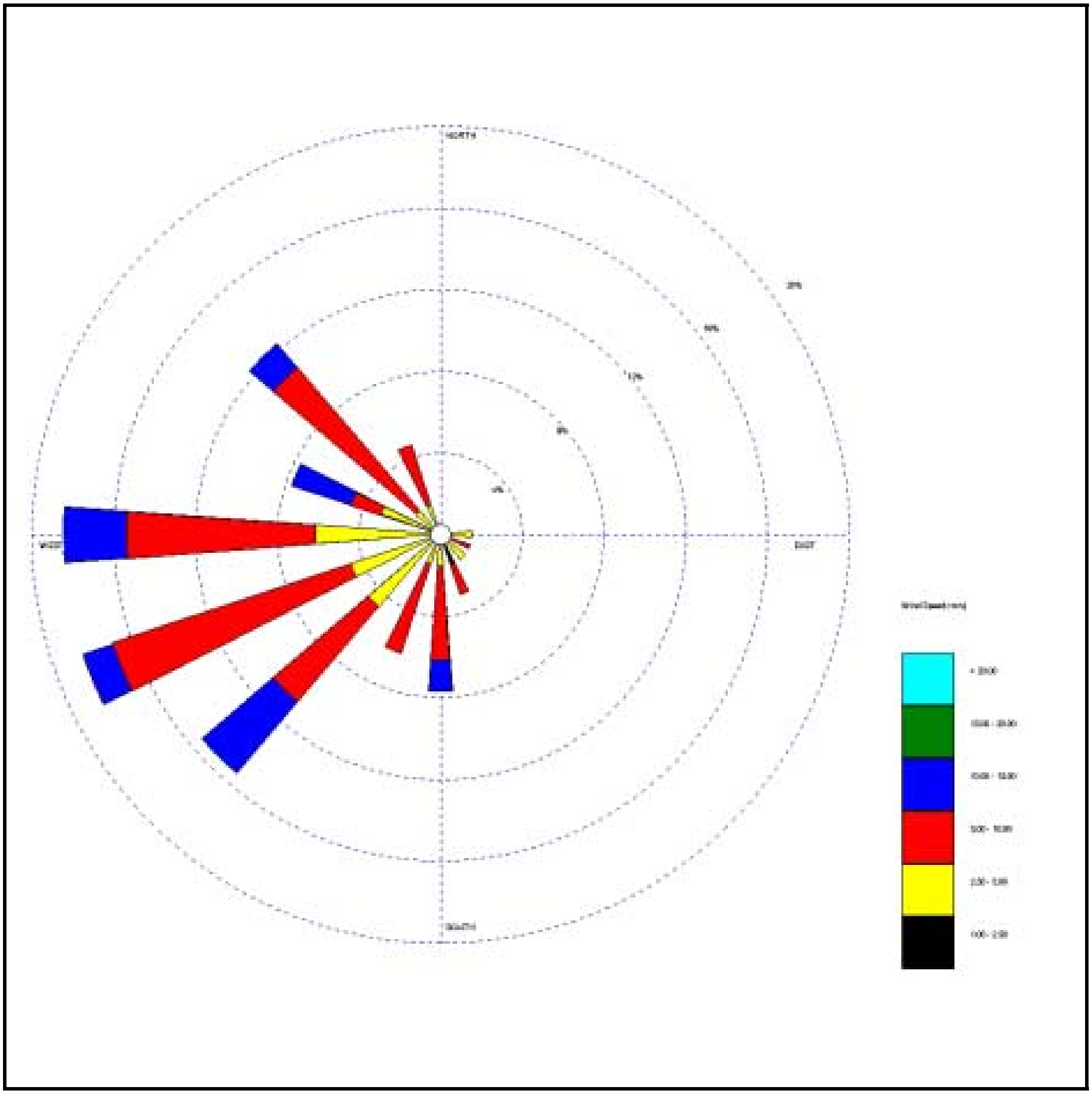


Figure 4-9. Wind rose frequency diagram for Oakland 500 mb winds for June to September 1990

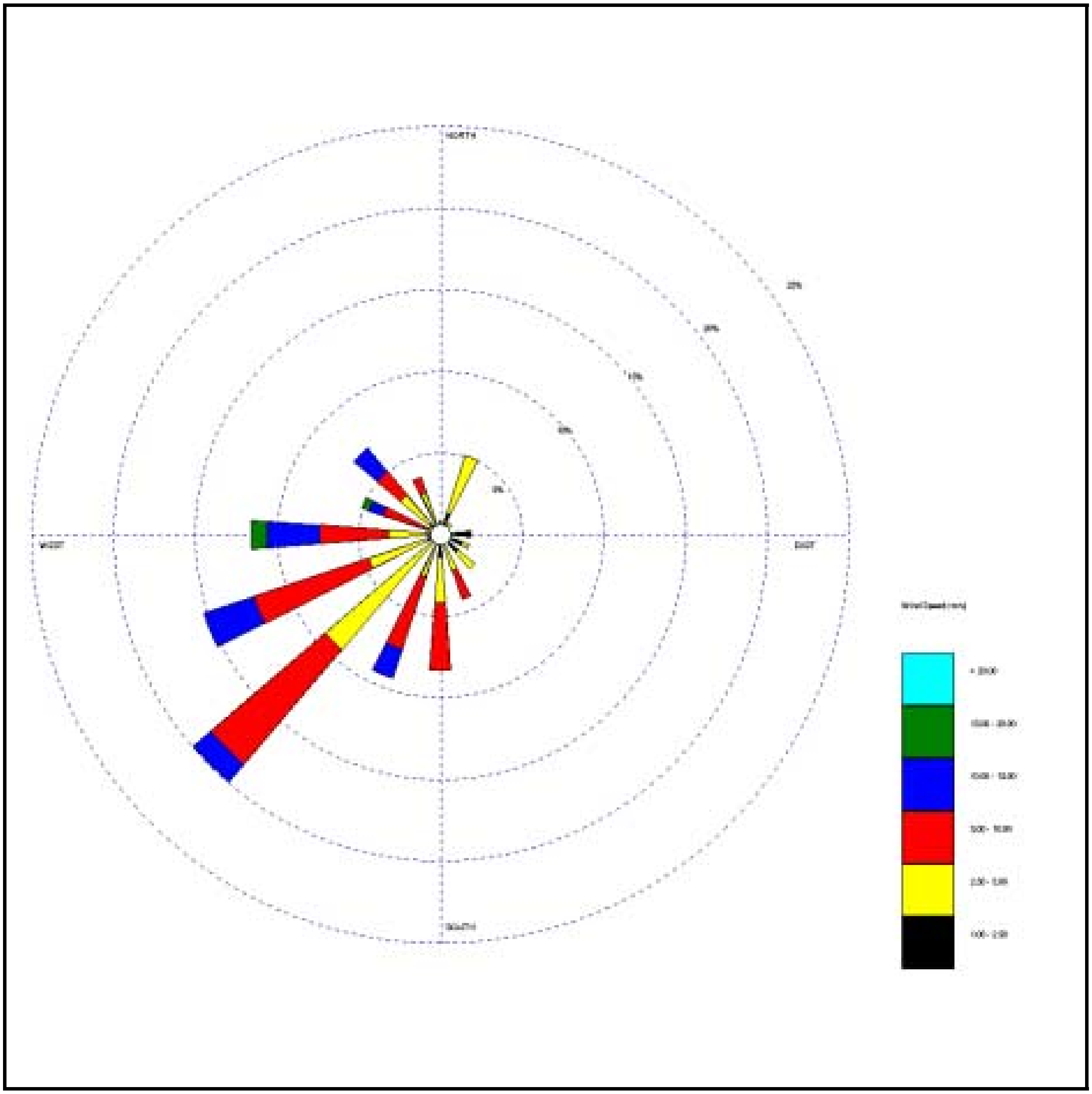


Figure 4-10. Wind rose frequency diagram for Oakland 500 mb winds for June to September 2000

5.0 SIGNIFICANT FINDINGS

The 1-hour cluster analysis put the AUSPEX and CCOS episode days into different clusters, suggesting that the September 17-21, 2000 episode had qualitatively different meteorology from the August 3-5, 1990 and July 30 to August 2, 2000 episodes.

The nocturnal jet and Fresno eddy development on the evening and morning of July 29 and July 30 were similar to the behavior observed in AUSPEX/SJVAQS, and consistent with the SARMAP conceptual wind flow model. The same can be said for the last evening/morning of the July 30 to August 2 episode as well but to a lesser extent. The typical pattern was temporarily disrupted during to the regression of the high pressure cell over western U.S.

The low-level meteorology measured both in the SV and SJV during the September 17 to 21 episode was very different than in the July 30 to August 2, 2000 episode and the two AUSPEX/SJVAQS episodes. A strong large-scale pressure gradient reversed the usual northwest regional flow pattern and overwhelmed local wind-field features.

Plots of daily maximum ozone concentrations and 500 mb heights during the June through September 2000 period indicates that high ozone is strongly correlated with high 500 mb heights at Oakland. A similar strong correlation exists between high ozone and high 850 mb temperatures.

No long extended episodes of ozone took place during the CCOS 2000 program. This could inhibit the development of high ozone concentrations because of the lack of multiday carry-over.

Examination of the synoptic-scale weather patterns for the four-month CCOS project period indicates that the transient ridges and troughs consistently moved in and out of the project area, with very few periods with static conditions. This is consistent with the observed lack of long uninterrupted ozone episodes.

Analysis of the 500 mb wind statistics for a 15 year period from 1986 through 2000 indicates that the CCOS program took place during a period similar to 1998, in which the winds tended to be more southerly than during most years. The southerly tendency is indicative of greater frequency of troughing conditions, which tend to reduce ozone strength and frequency.

6.0 REFERENCES

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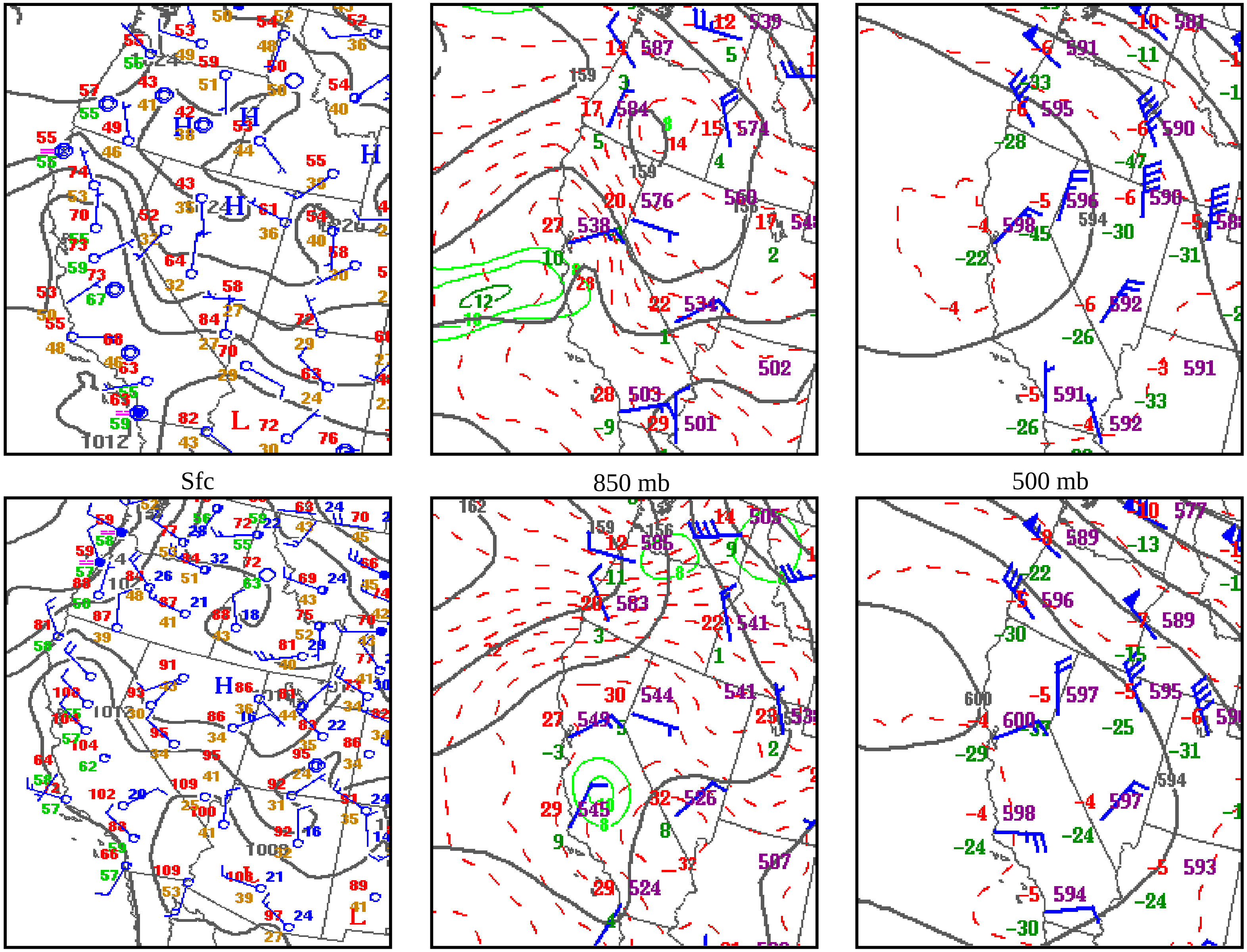
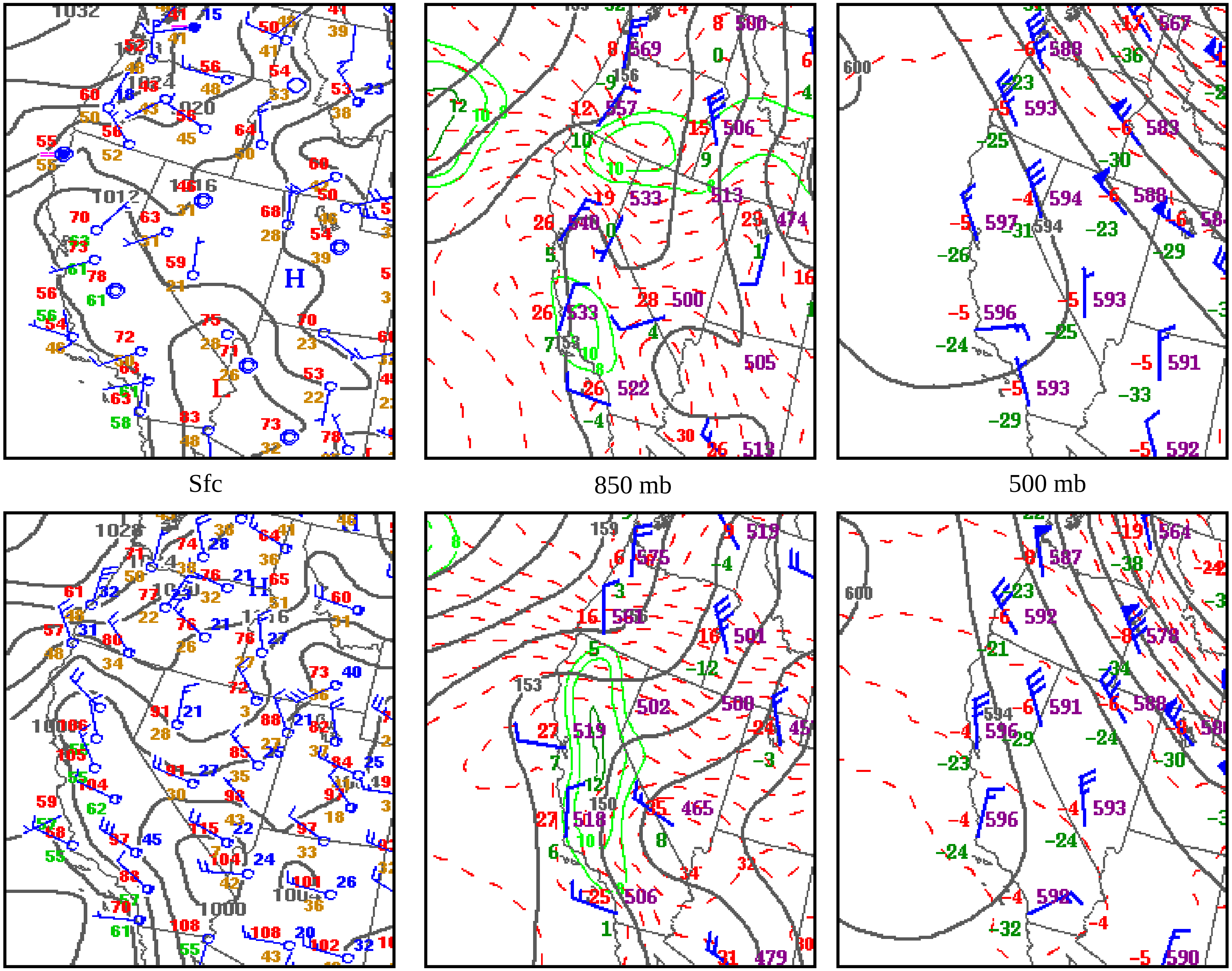
APPENDIX A

Synoptic Weather Maps



Synoptic Weather Maps for 06/14/00 (top panel depicts morning, lower panel depicts afternoon)



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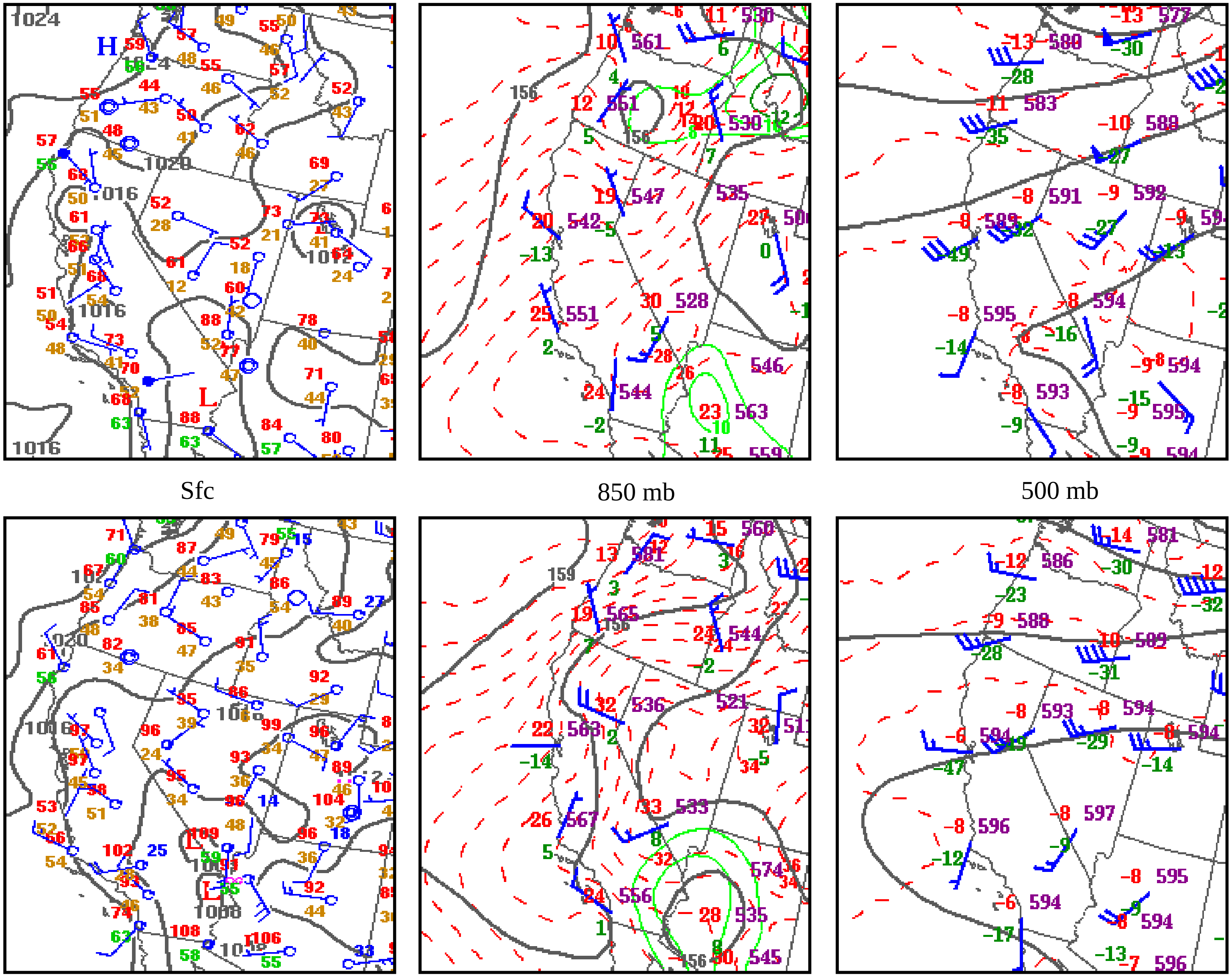

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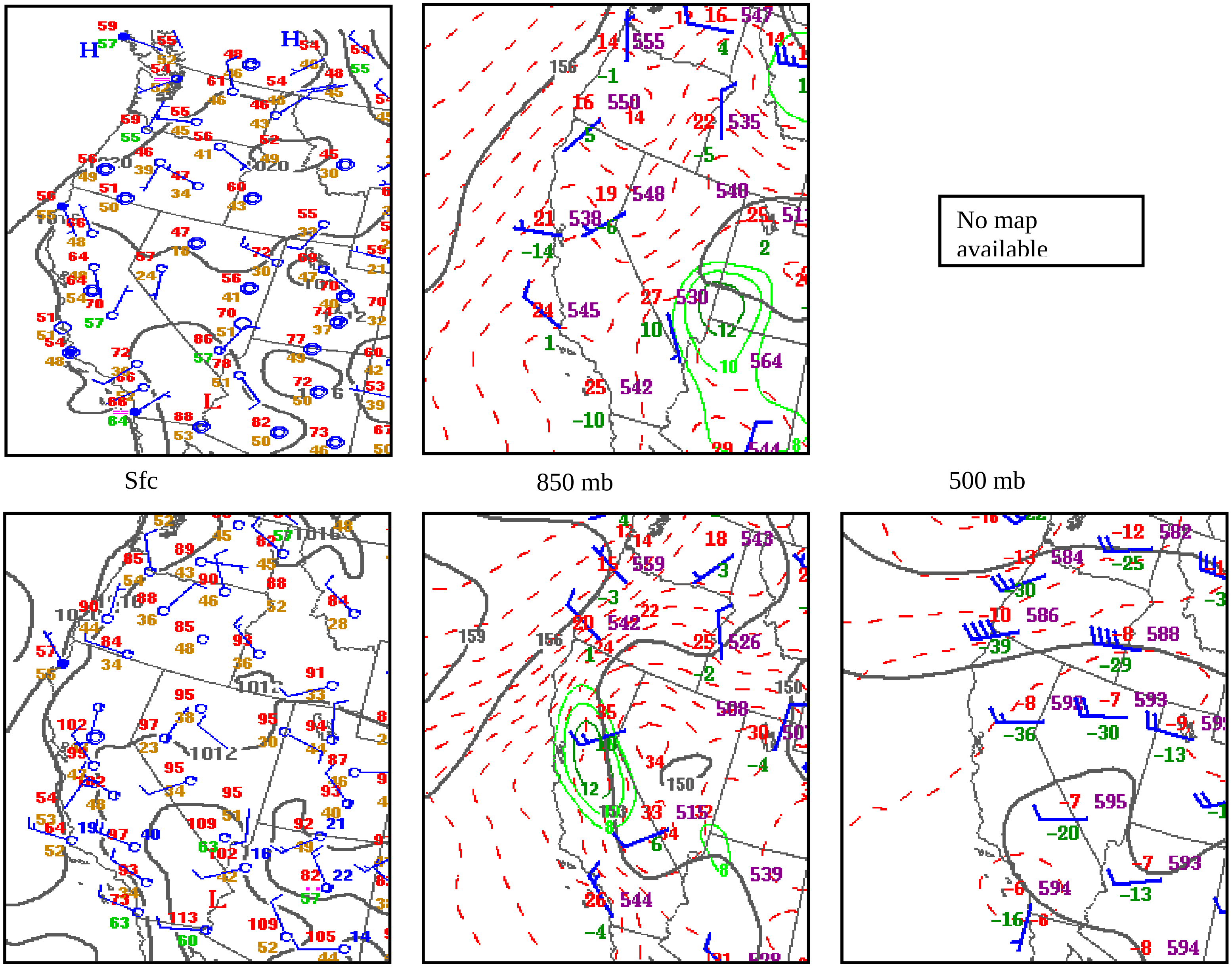

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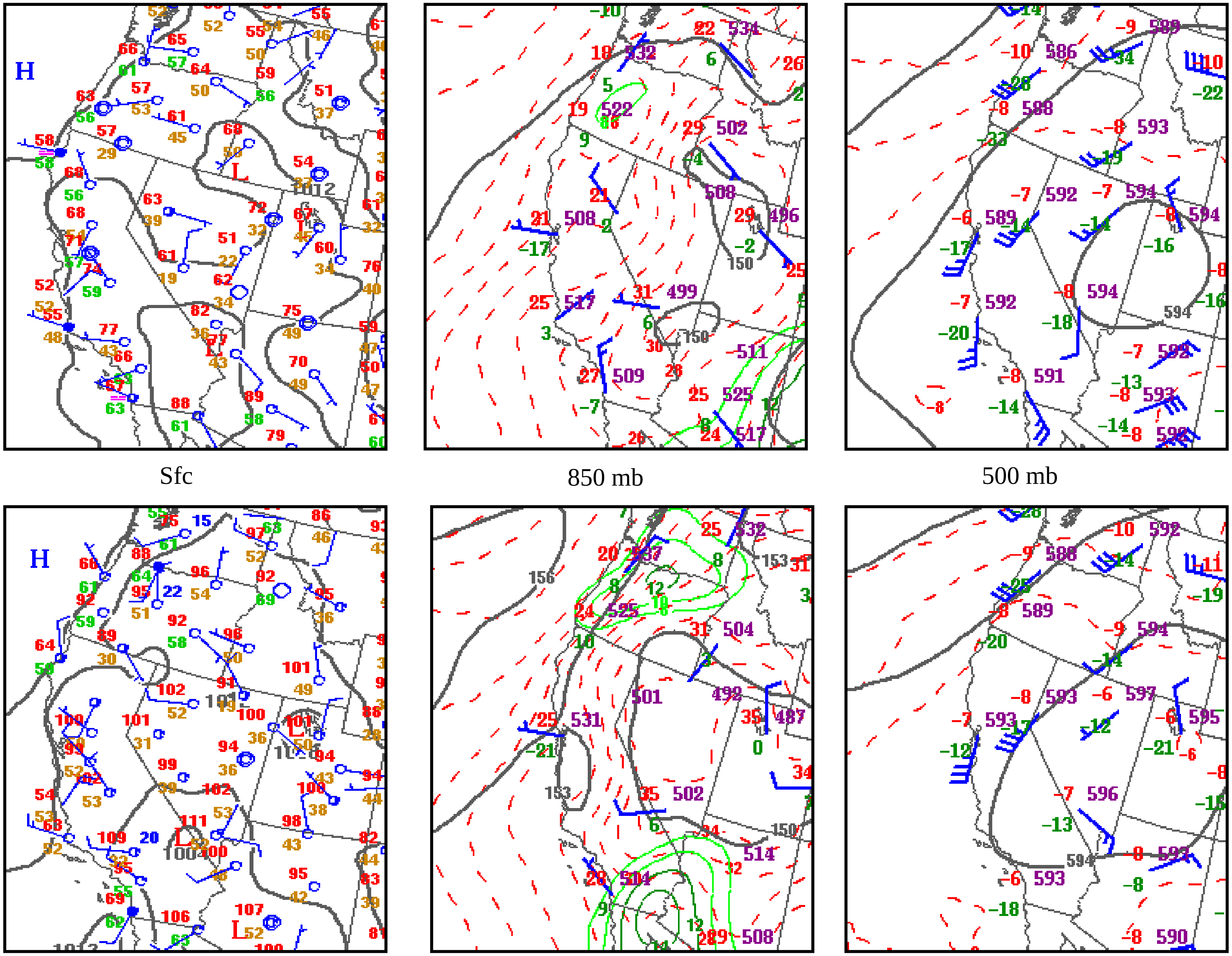

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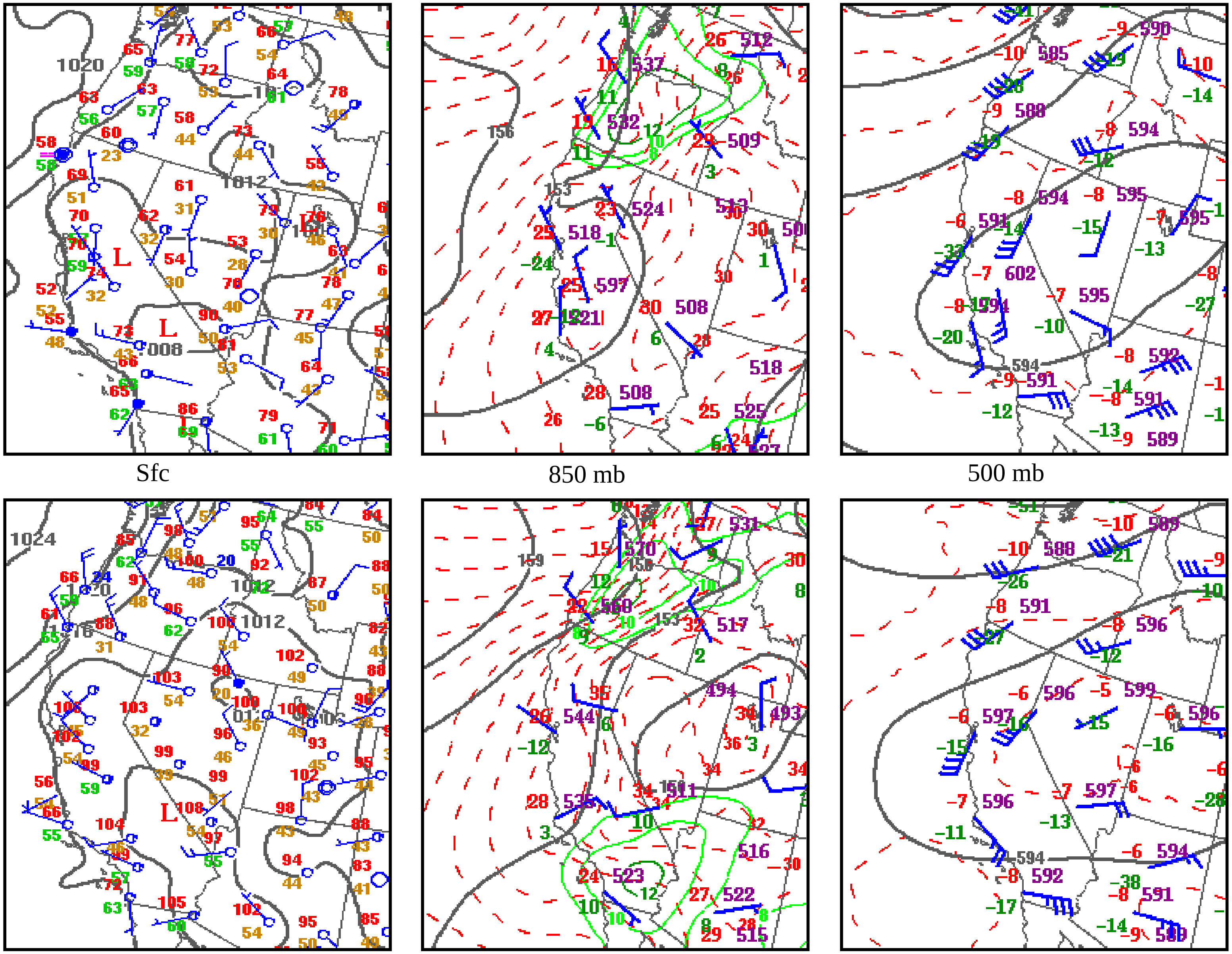

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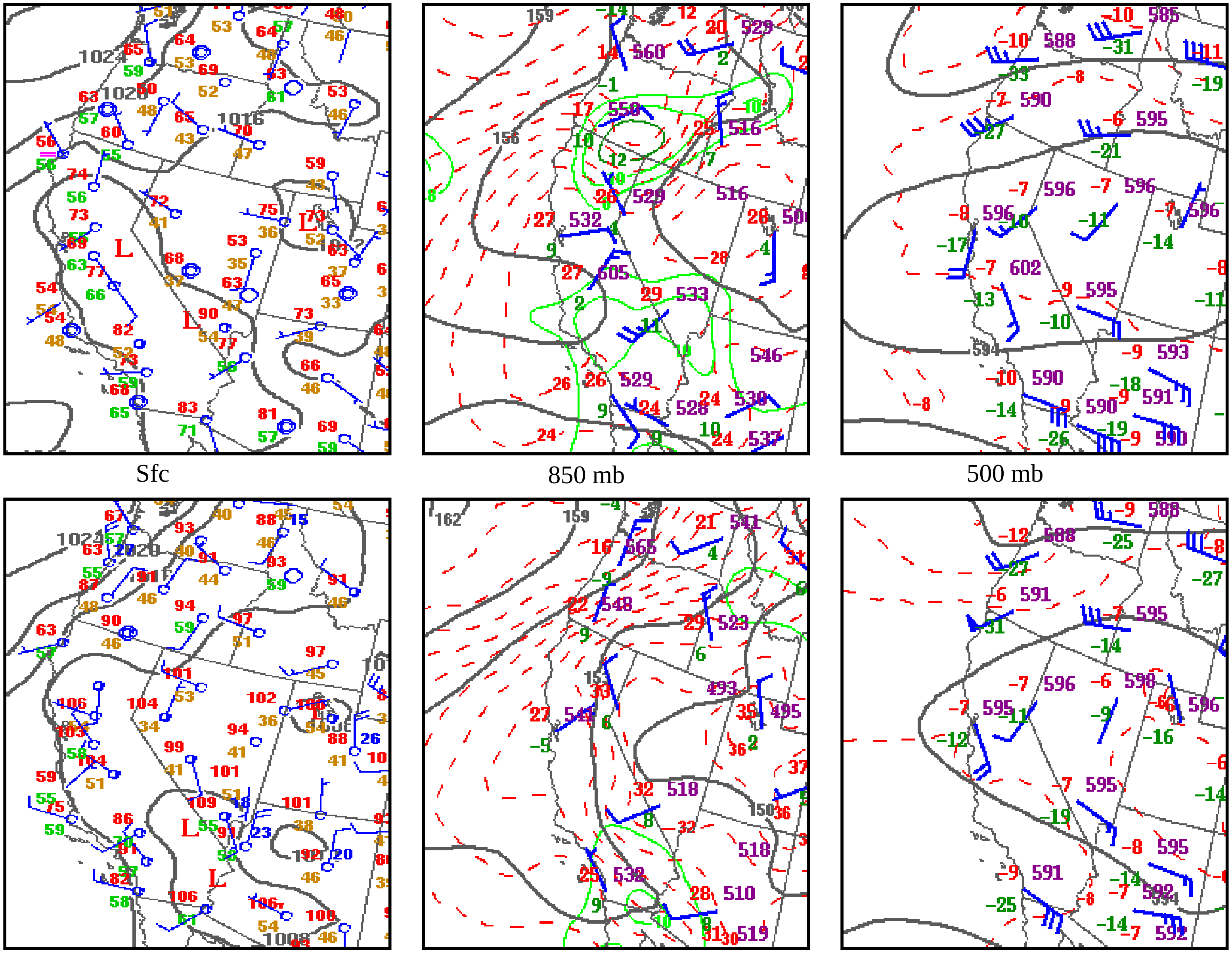

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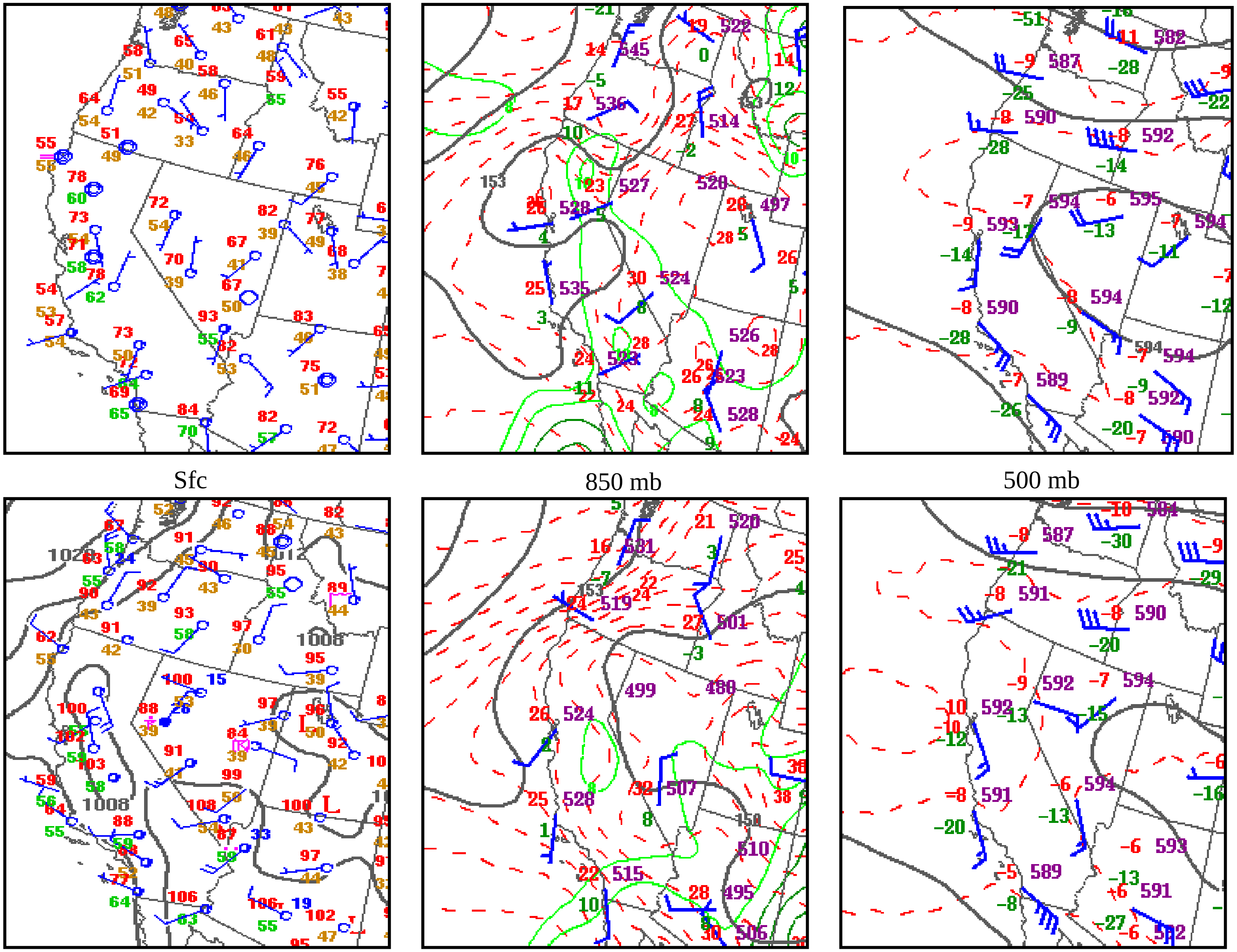
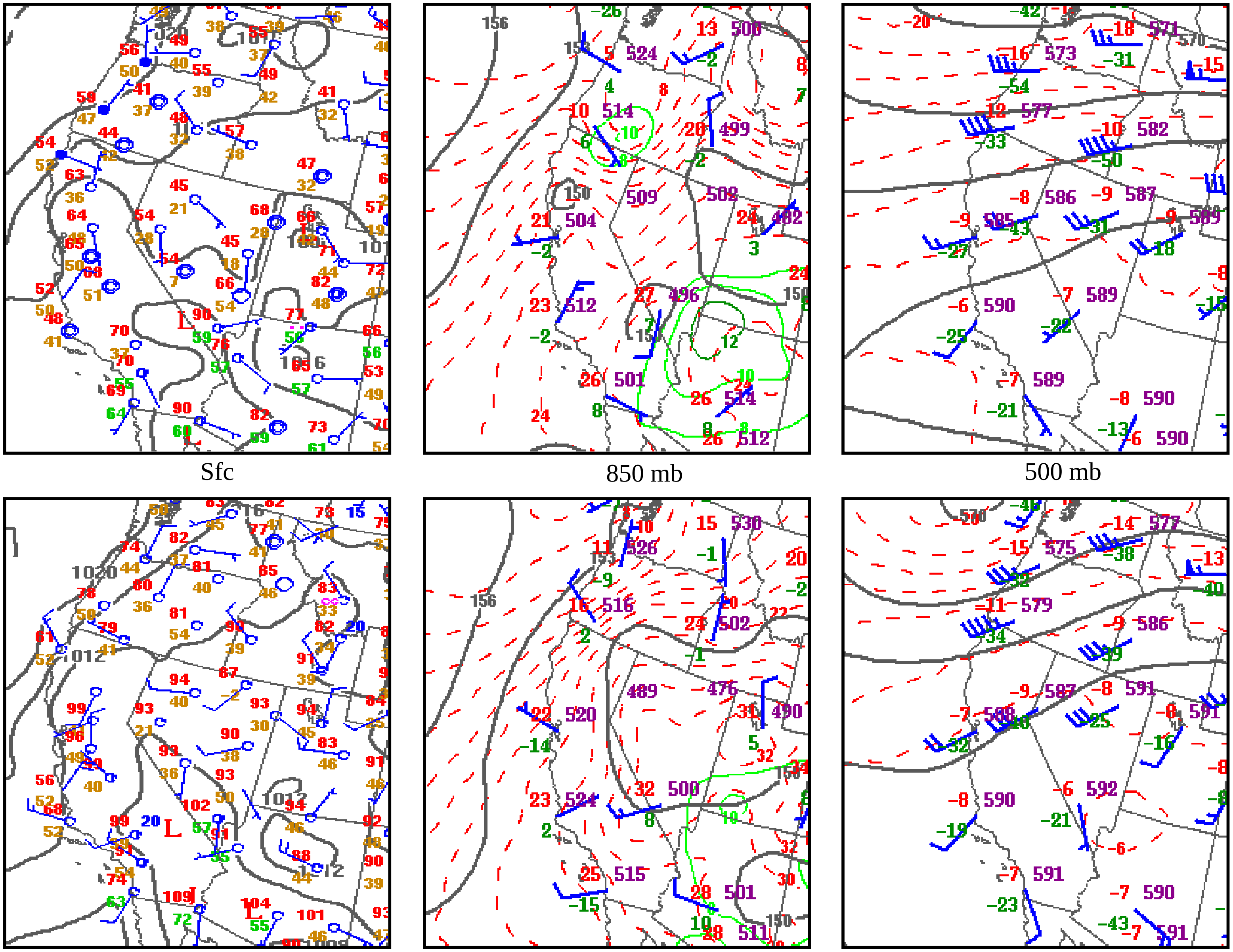


Synoptic Weather Maps for 08/02/00 (top panel depicts morning, lower panel depicts afternoon)



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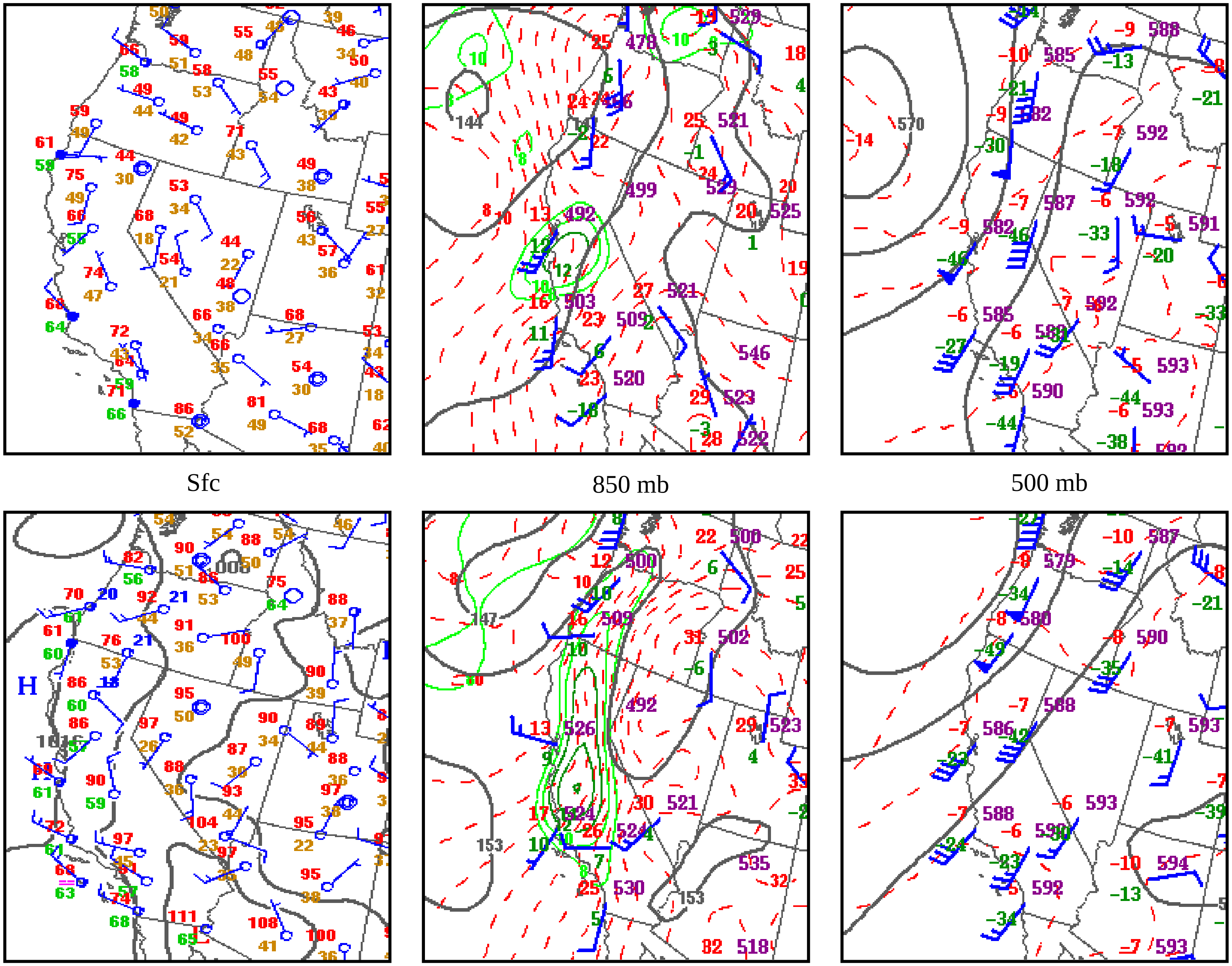
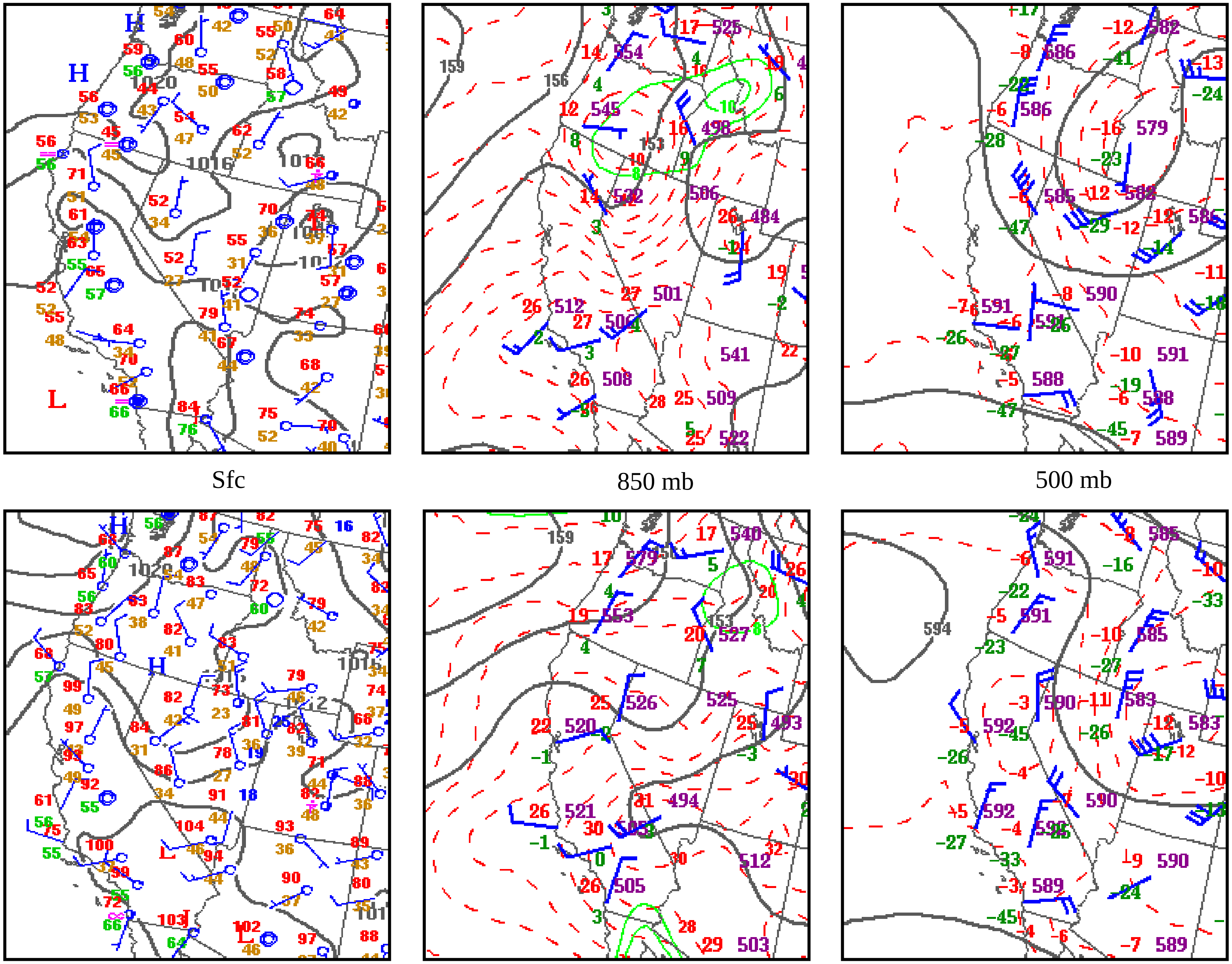


Synoptic Weather Maps for 09/14/00 (top panel depicts morning, lower panel depicts afternoon)



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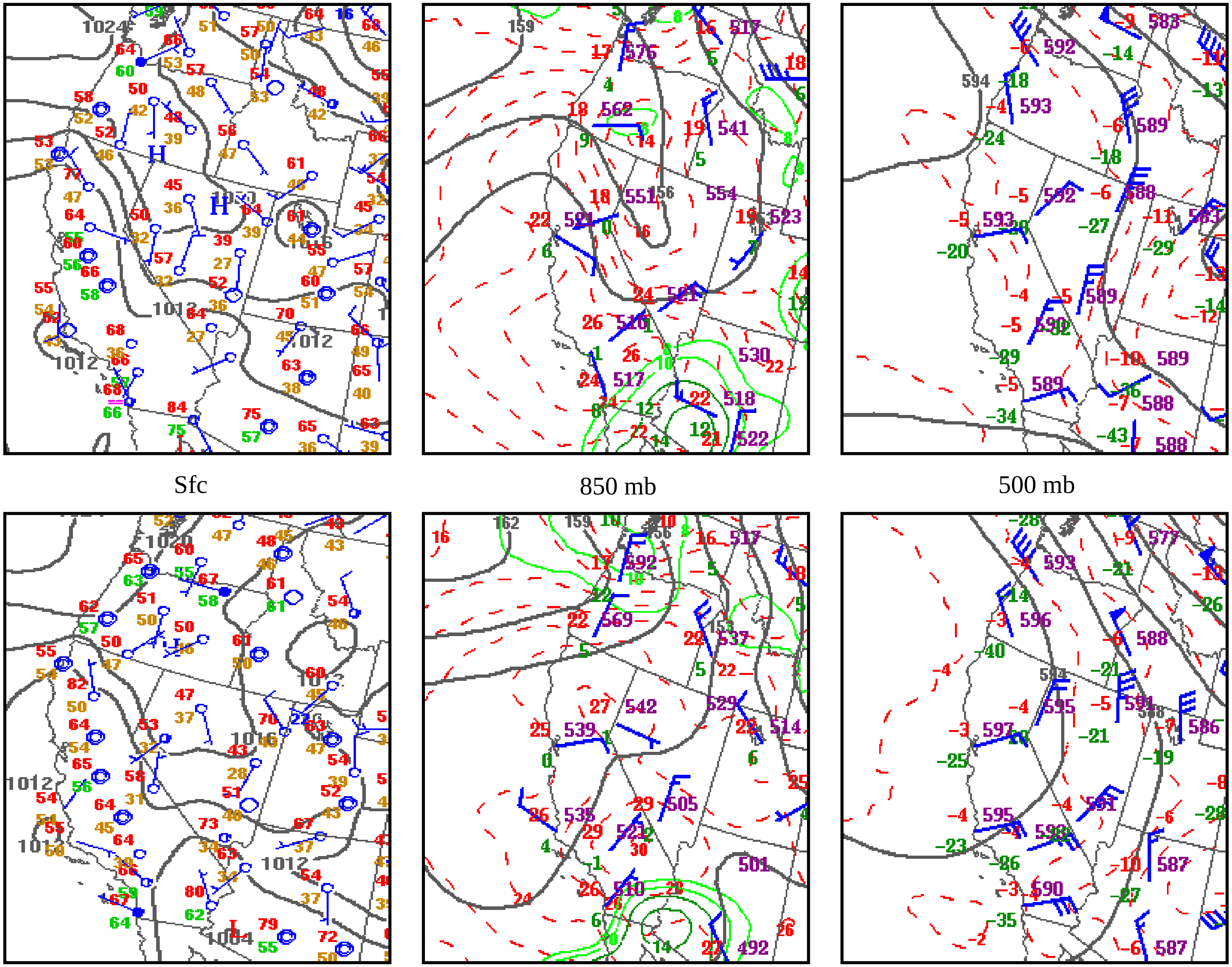

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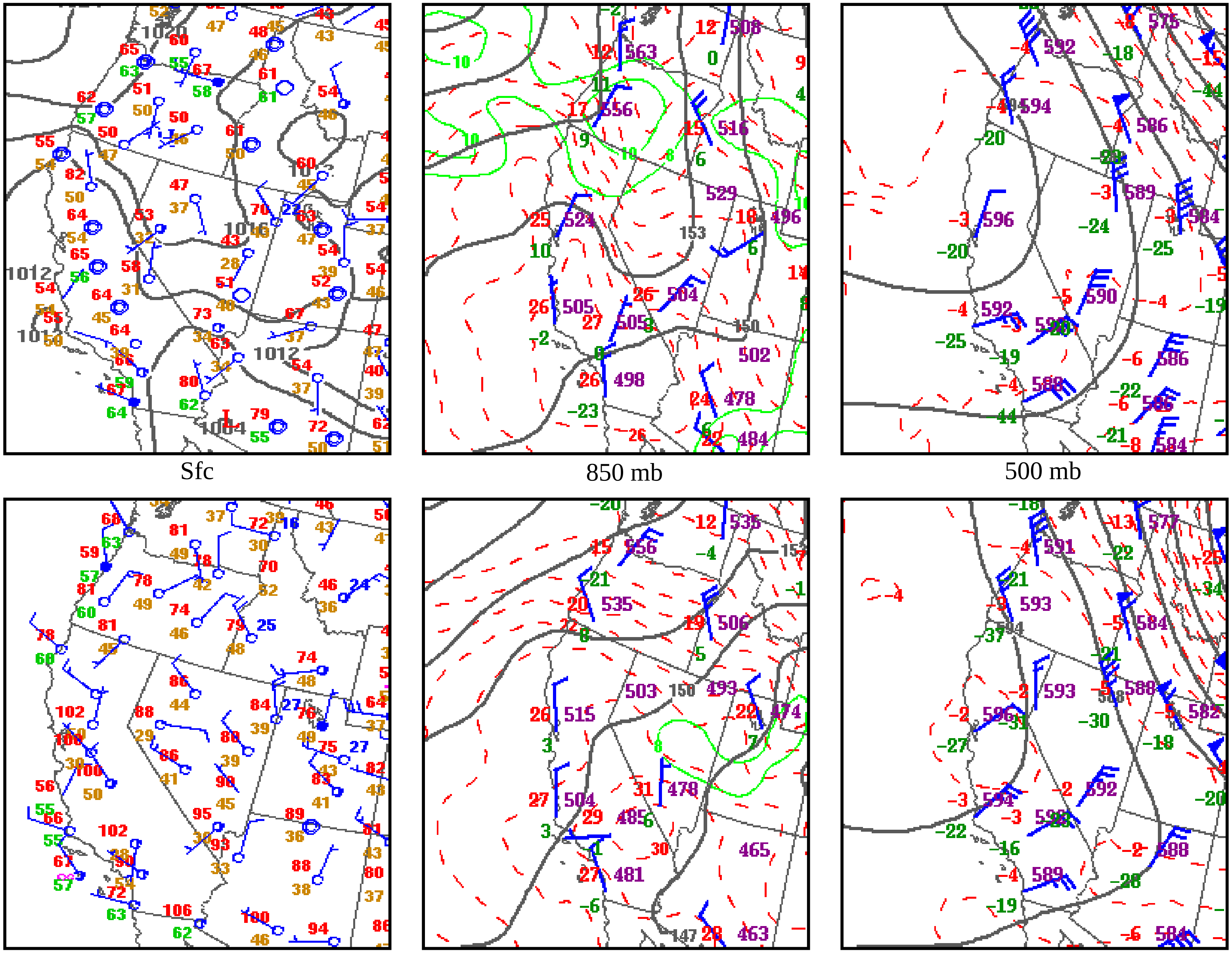
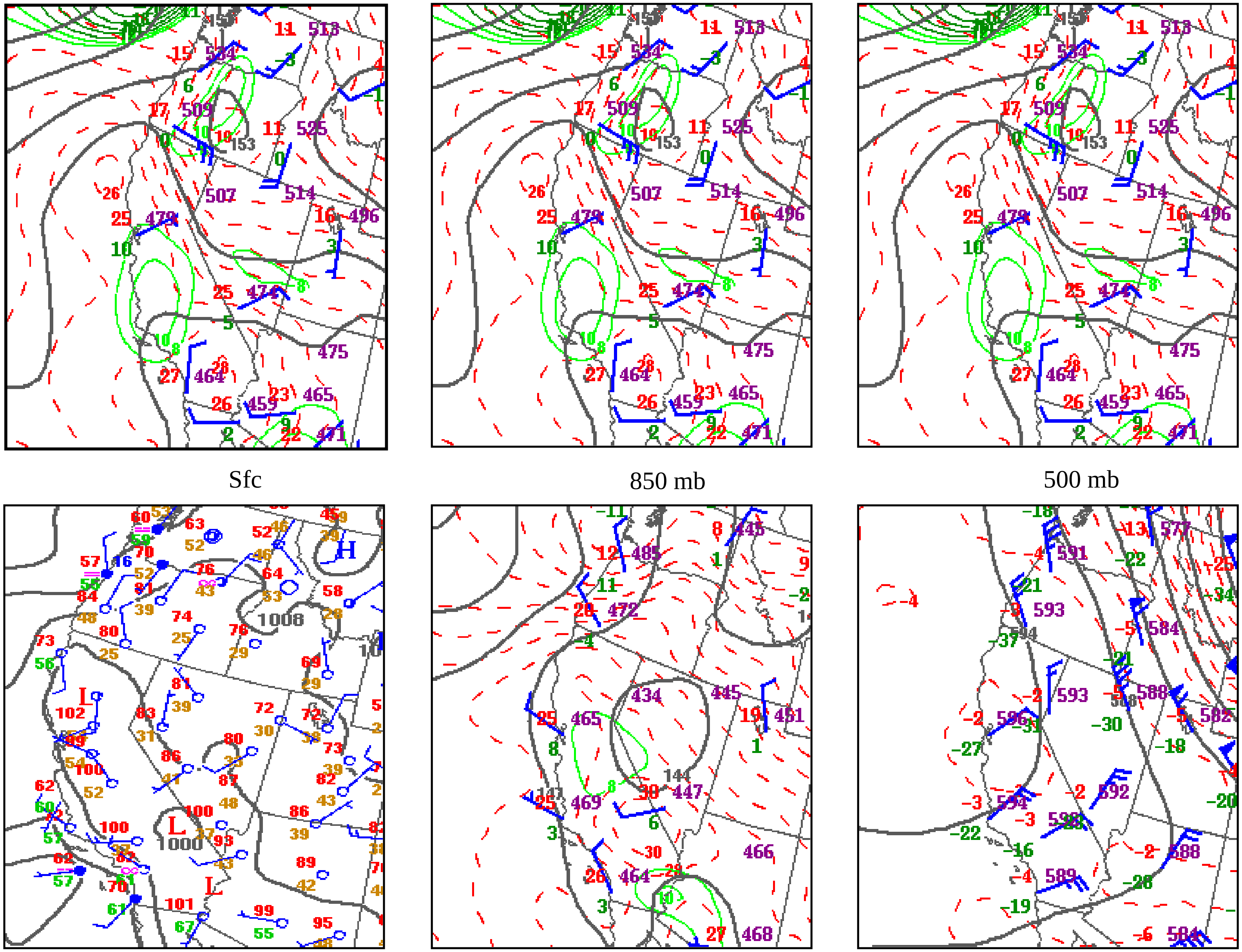
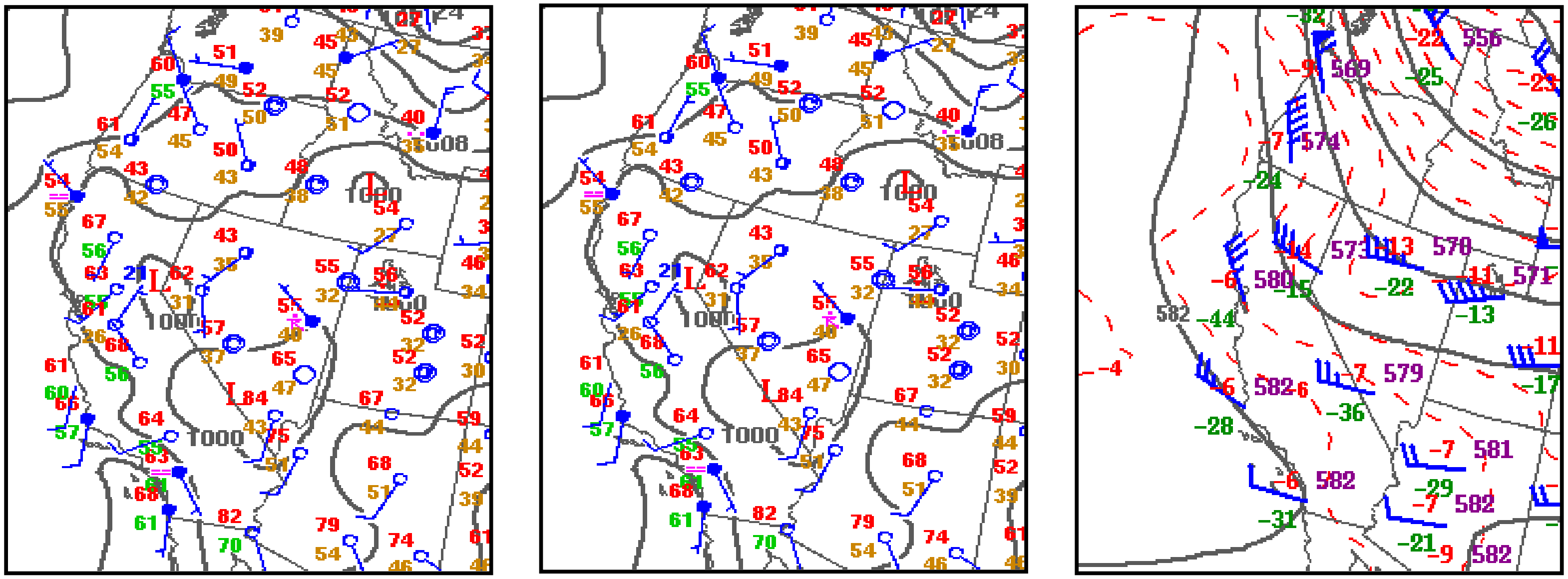


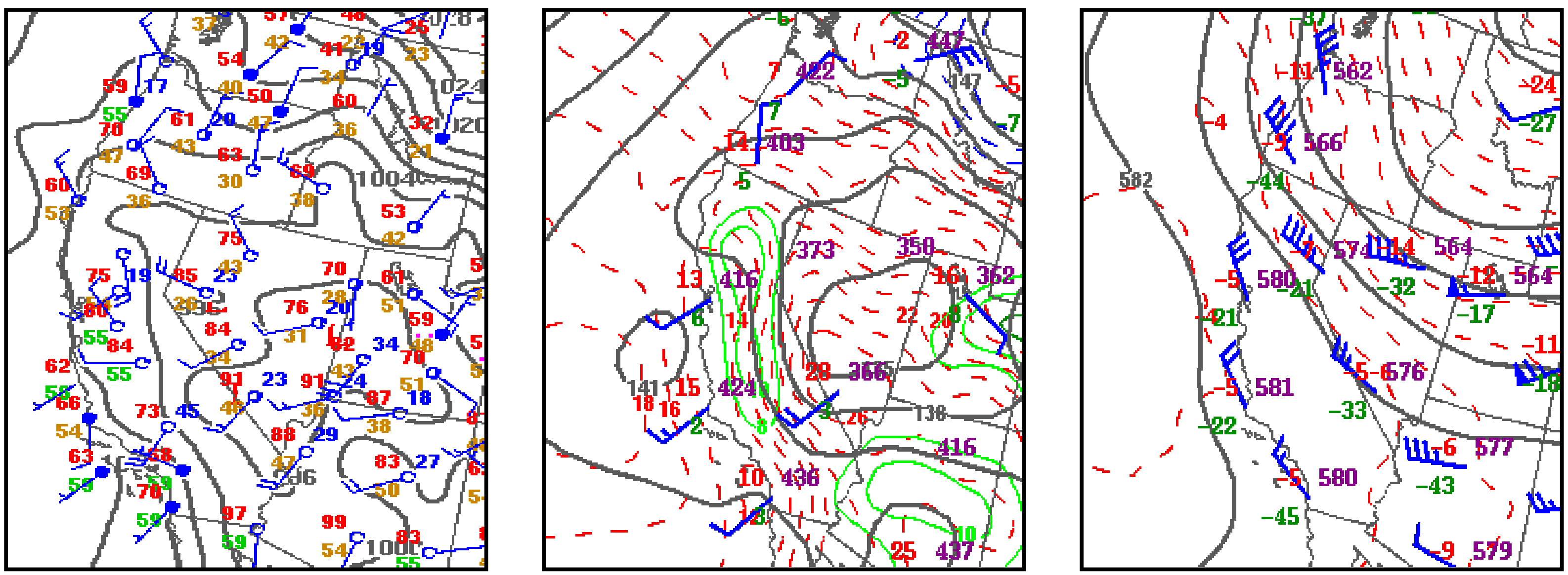
Synoptic Weather Maps for 09/19/00 (top panel depicts morning, lower panel depicts afternoon)



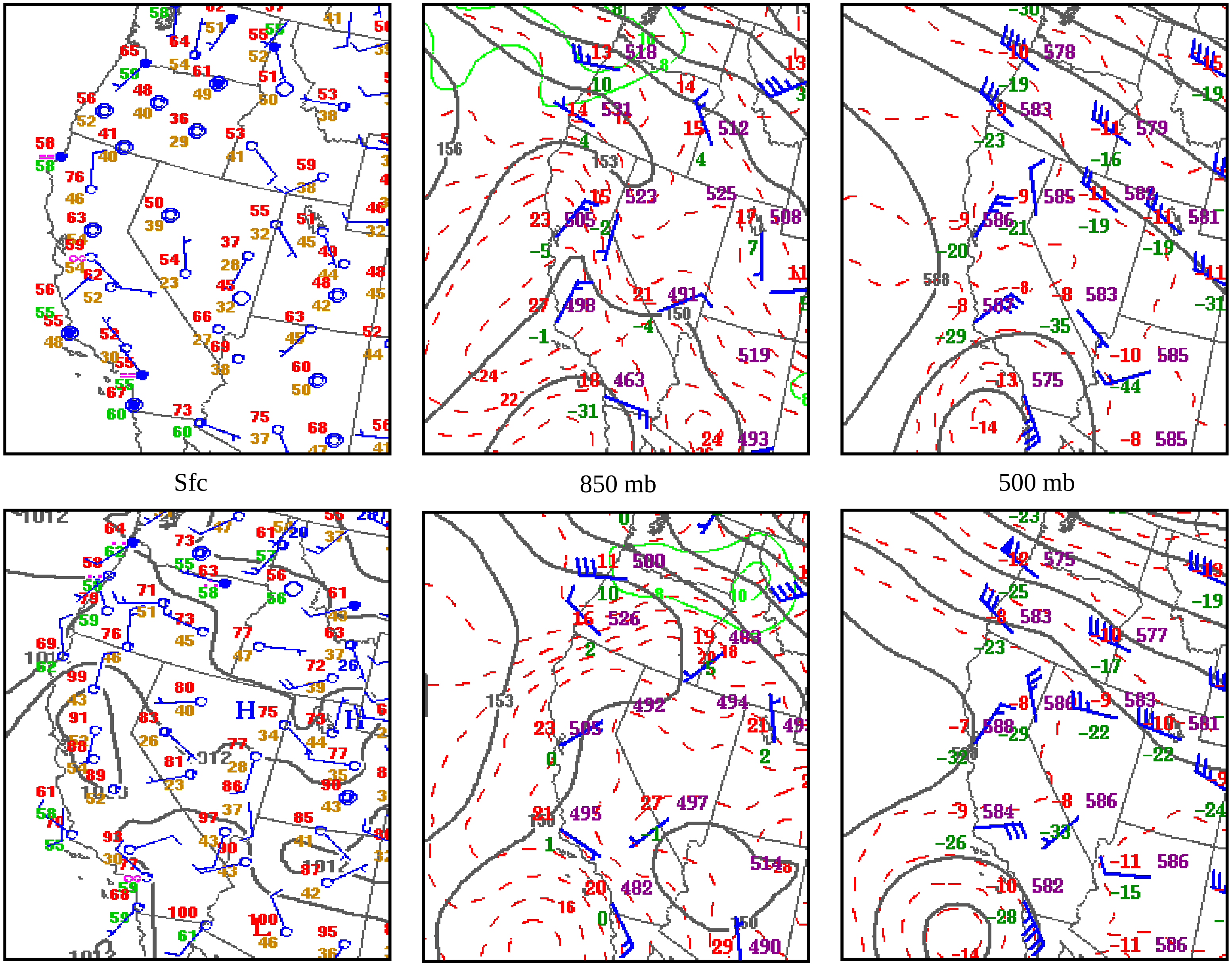
Synoptic Weather Maps for 09/20/00 (top panel depicts morning, lower panel depicts afternoon)



Sfc 850 mb 500 mb



Synoptic Weather Maps for 09/21/00 (top panel depicts morning, lower panel depicts afternoon)



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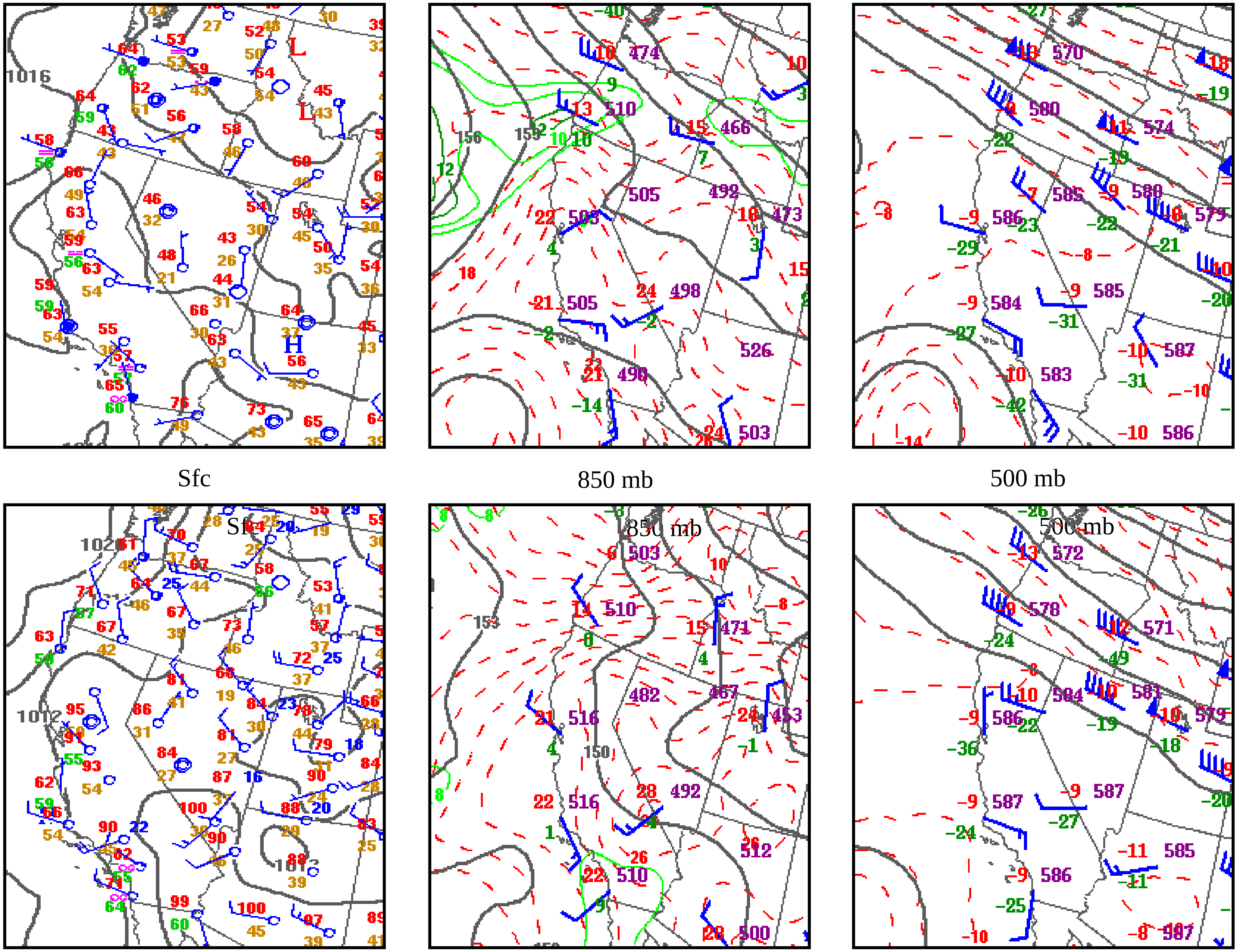

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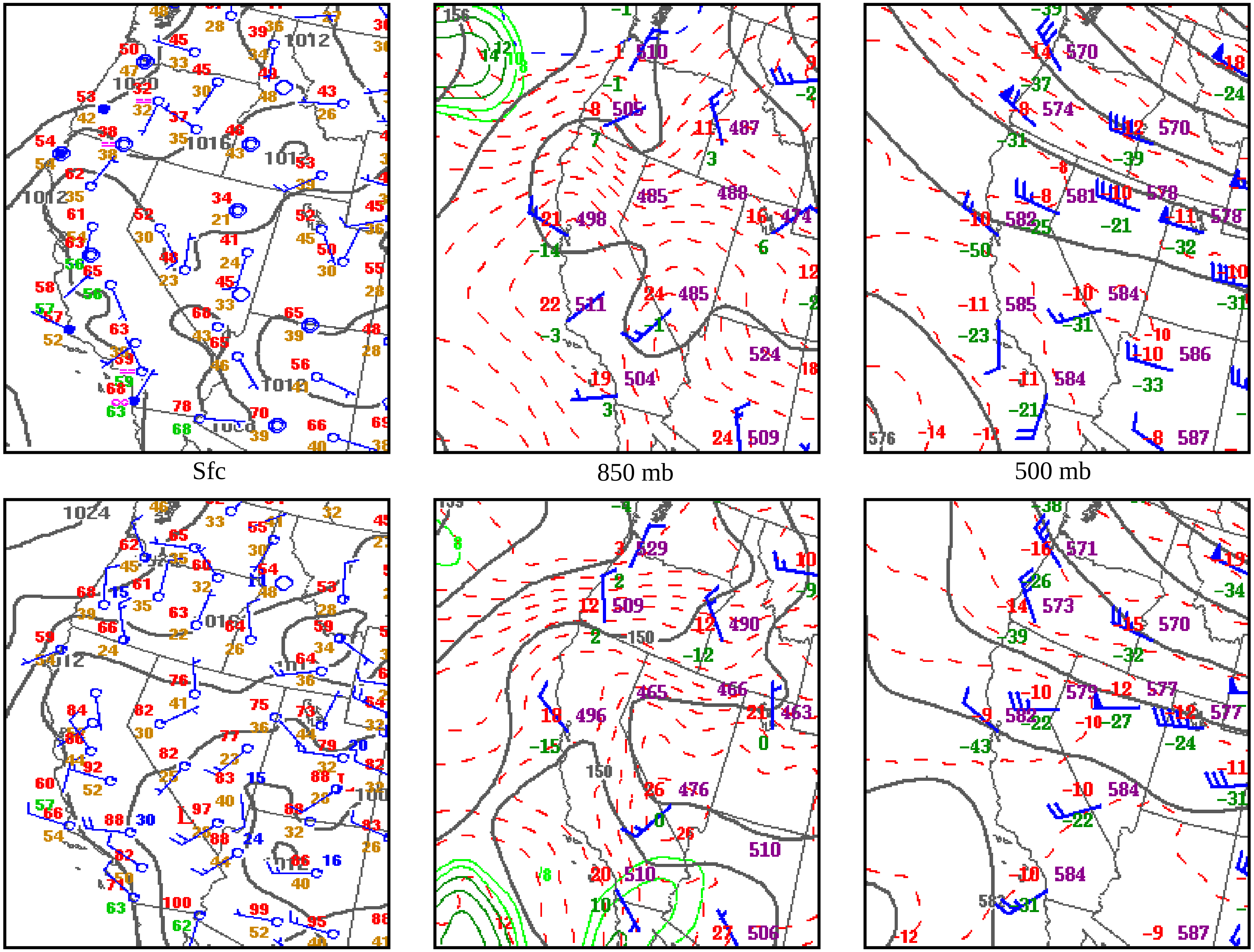
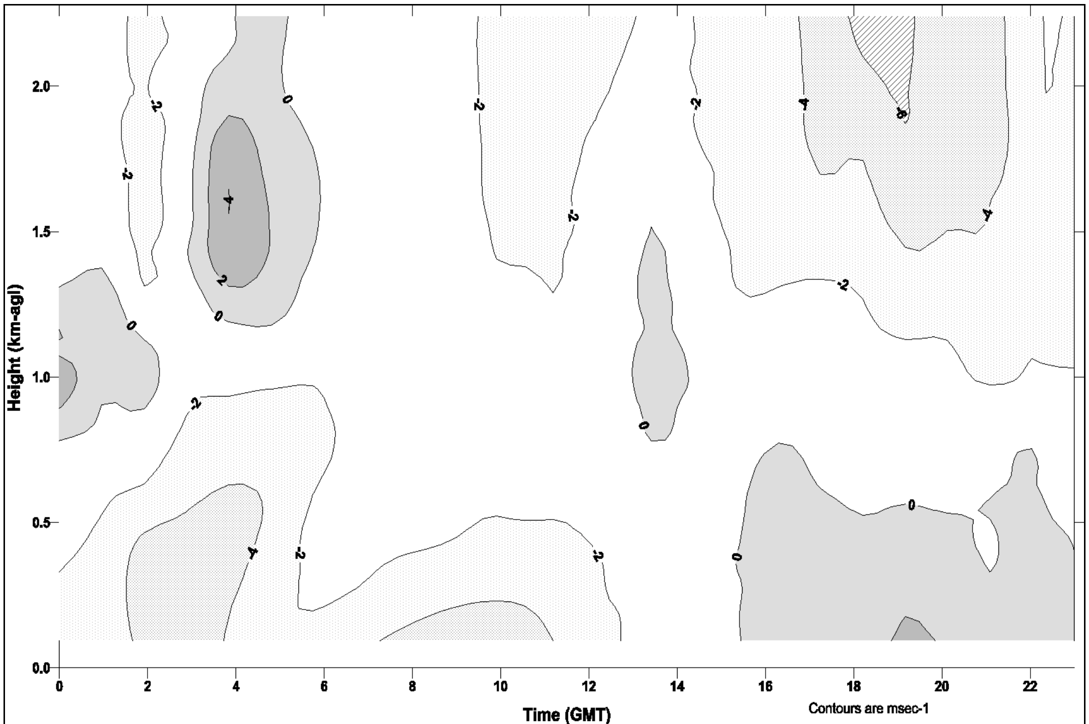


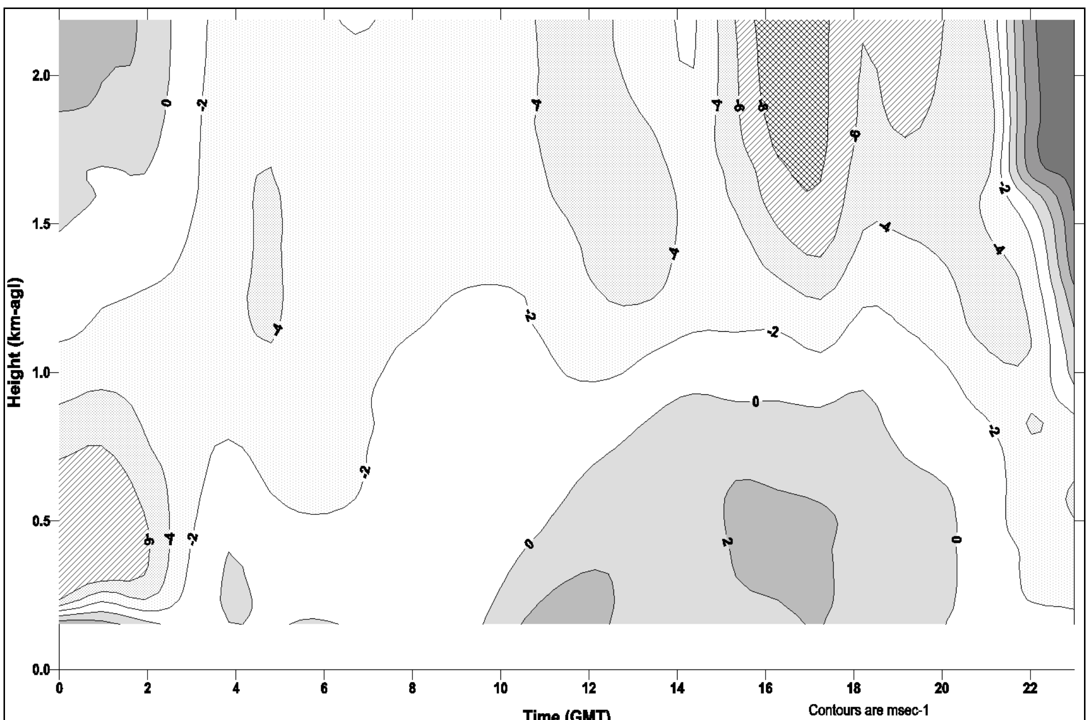
Synoptic Weather Maps for 10/2/00 (top panel depicts morning, lower panel depicts afternoon)

APPENDIX B

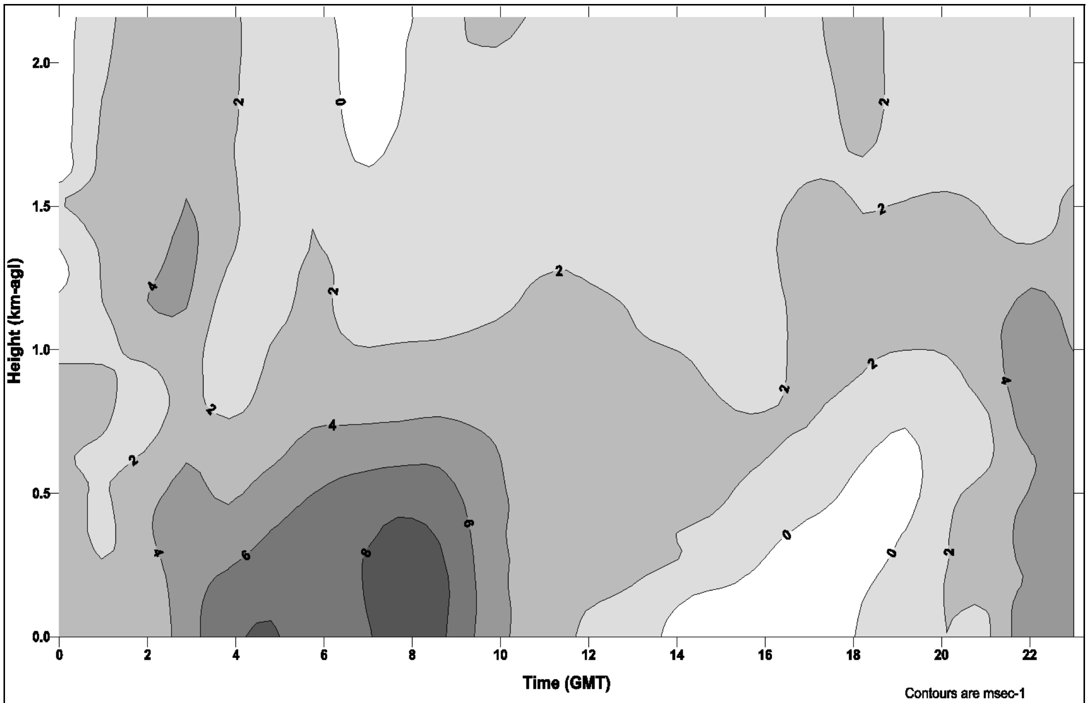
Winds Aloft



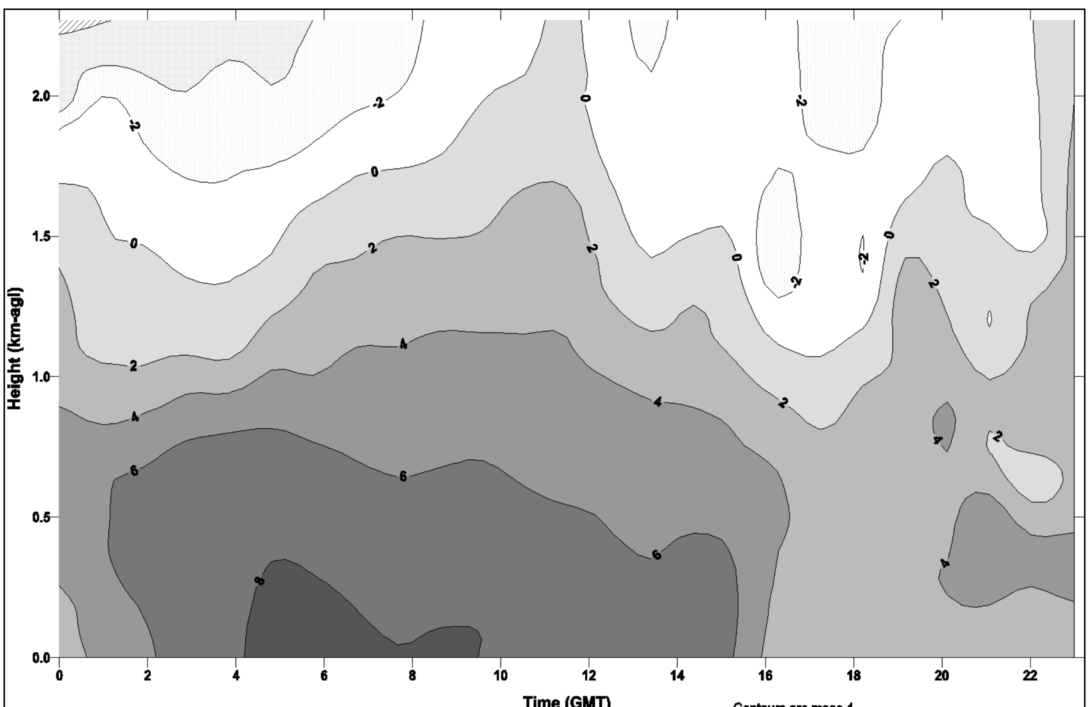
NW to SE Component of Winds Aloft
Pleasant Grove July 30, 2000



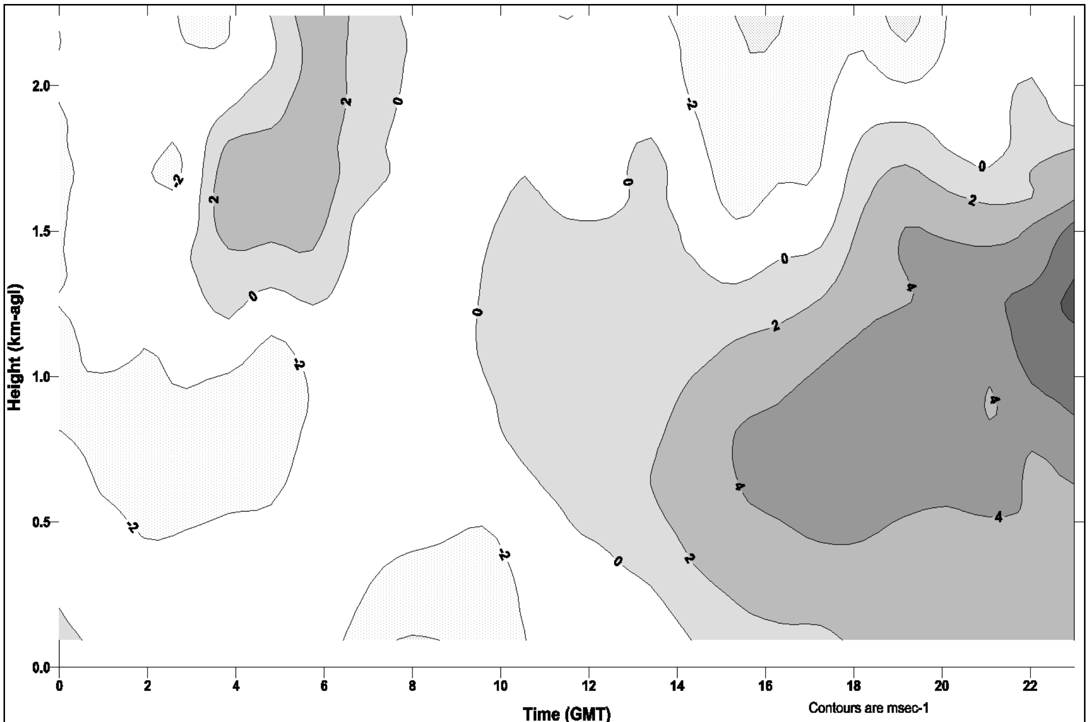
NW to SE Component of Winds Aloft
Arbuckle July 30, 2000



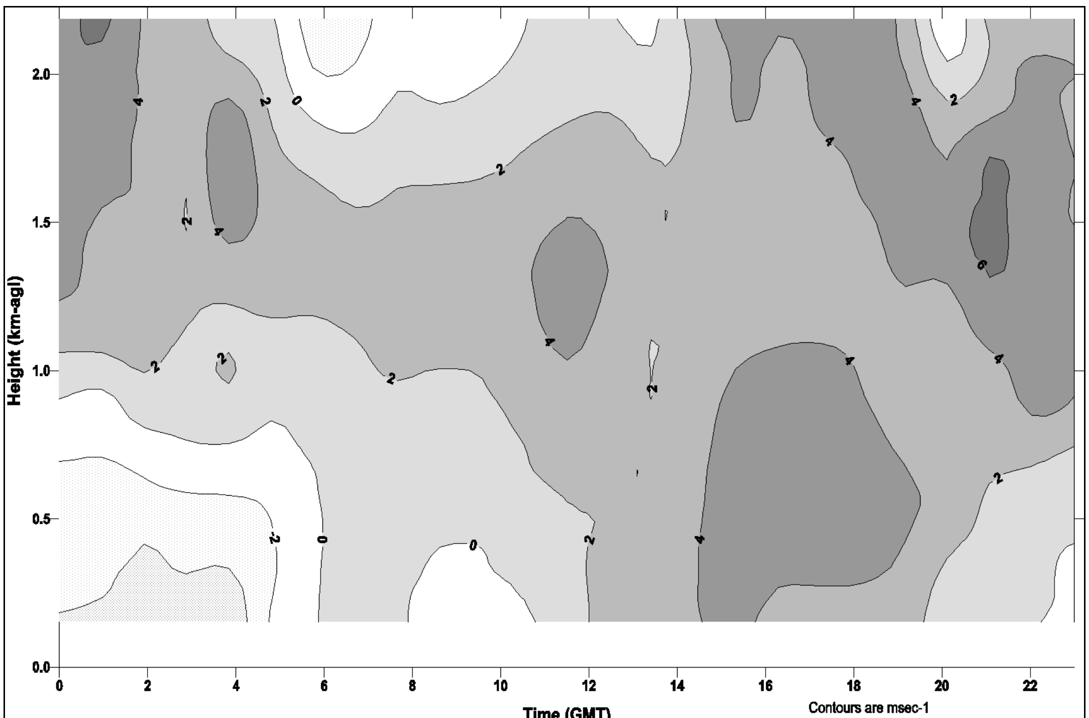
NW to SE Component of Winds Aloft
Visalia July 30, 2000



NW to SE Component of Winds Aloft
Waterford July 30, 2000



NW to SE Component of Winds Aloft
Pleasant Grove July 31, 2000



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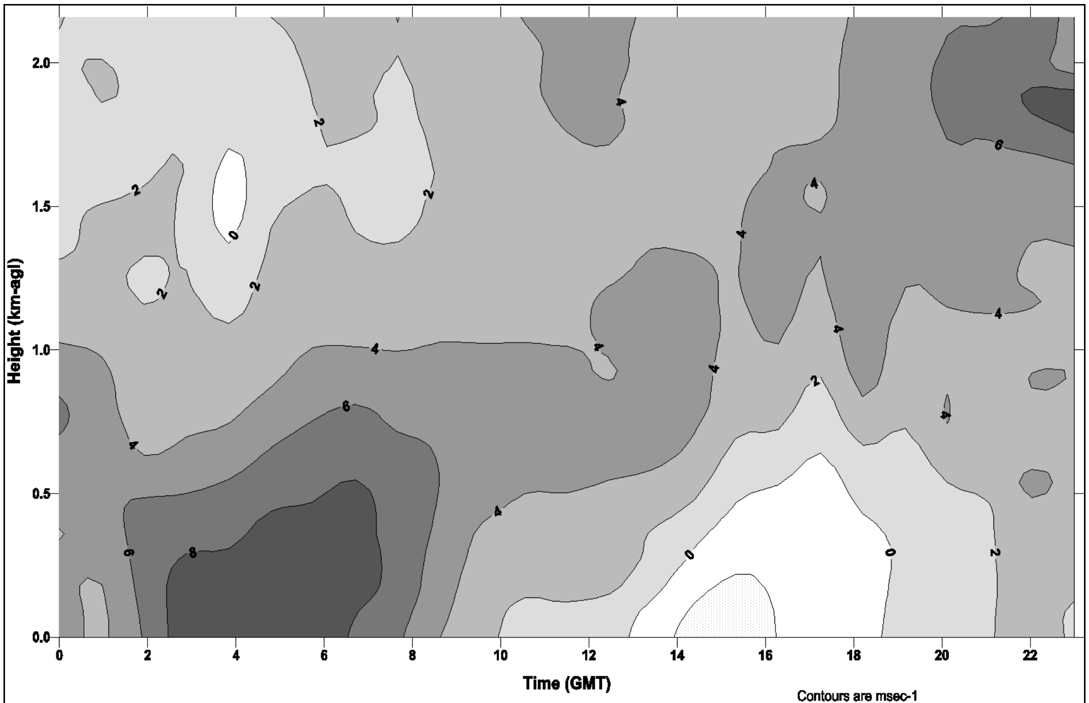

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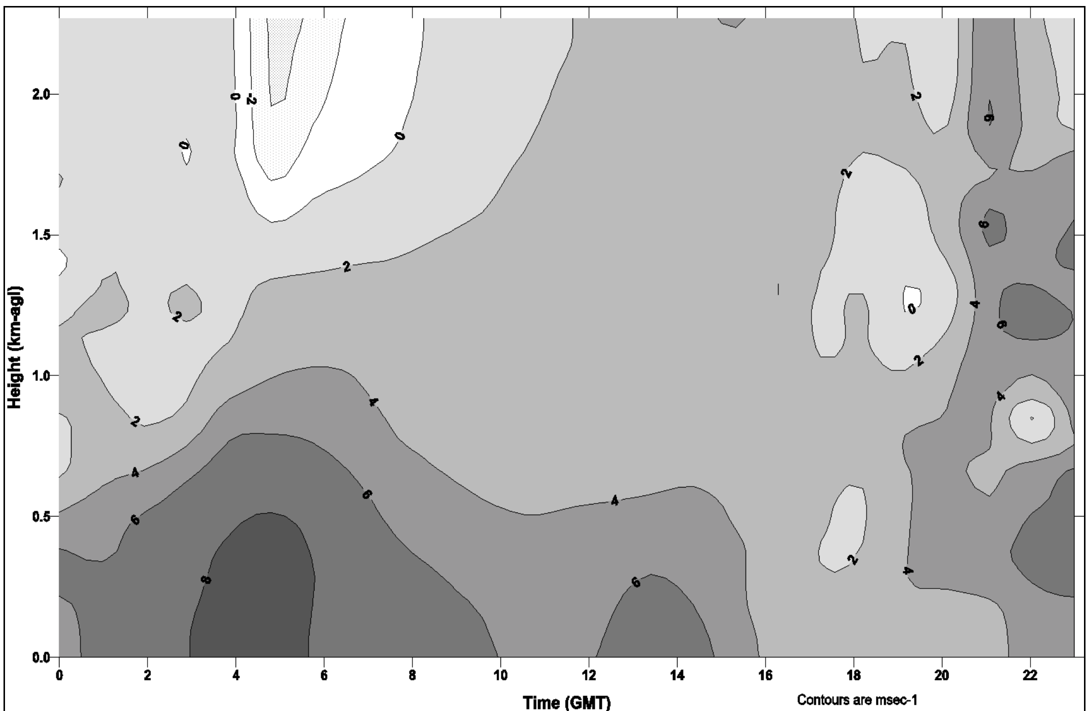
Visalia July 31, 2000



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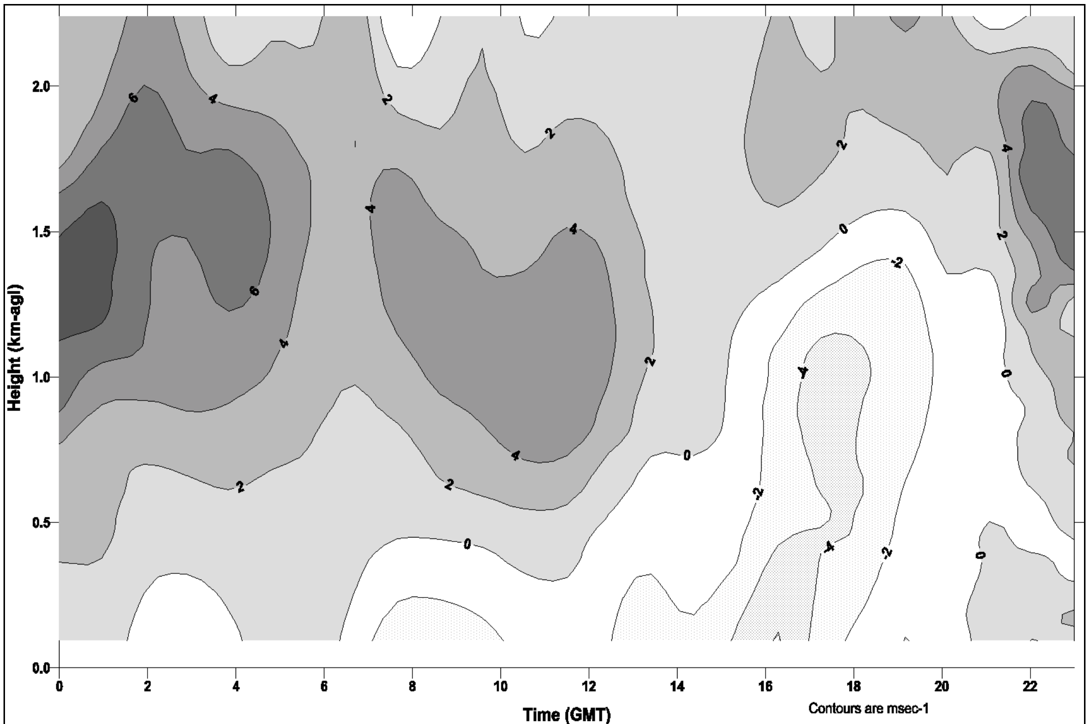
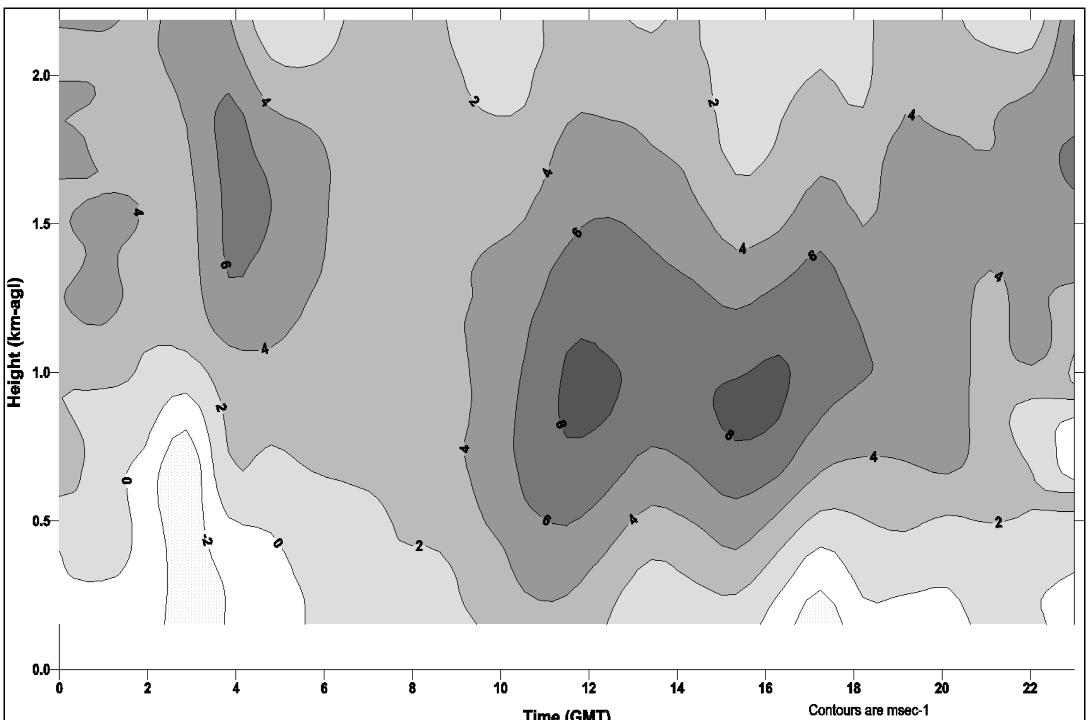
Waterford July 31, 2000



NW to SE Component of Winds Aloft
Pleasant Grove August 1, 2000



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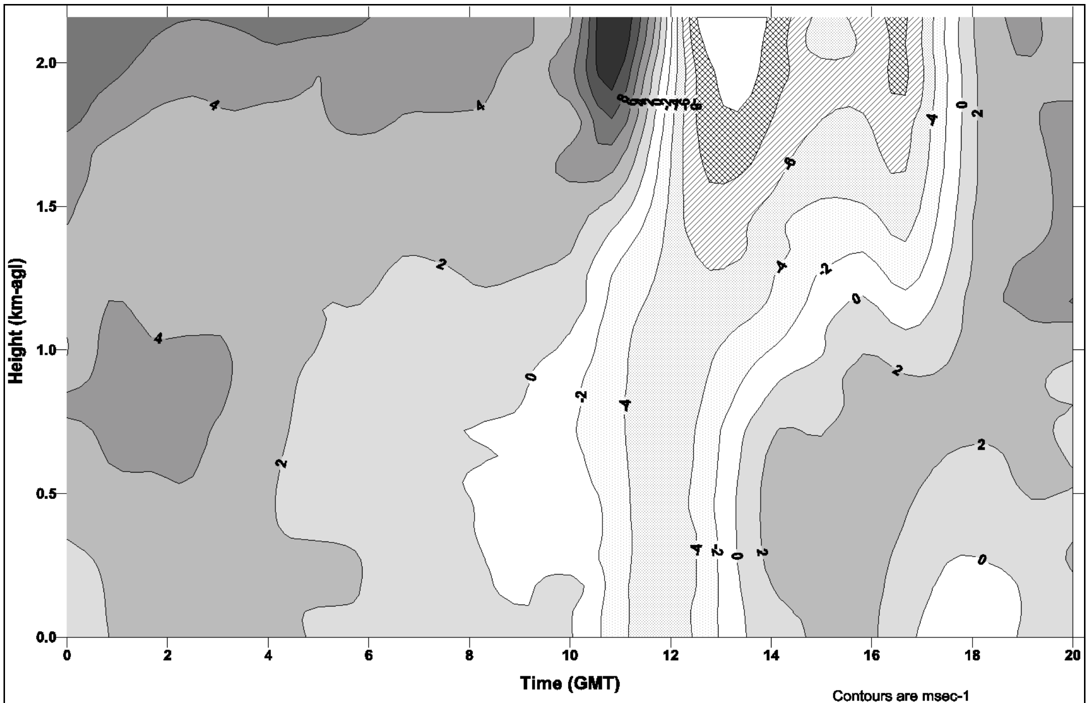

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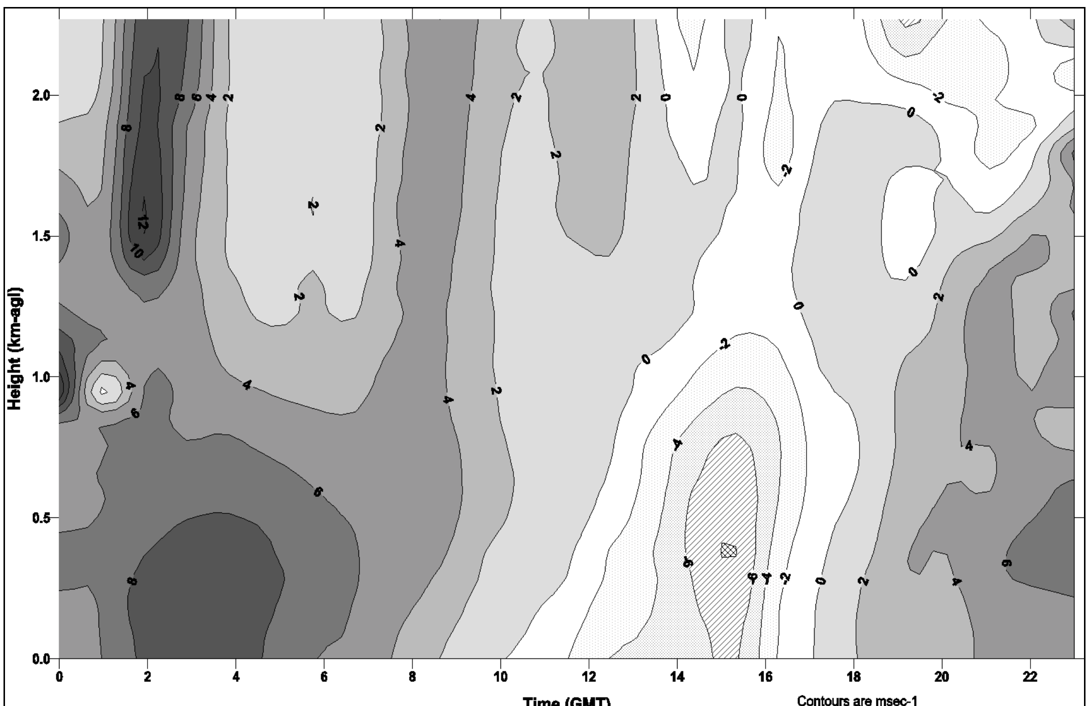

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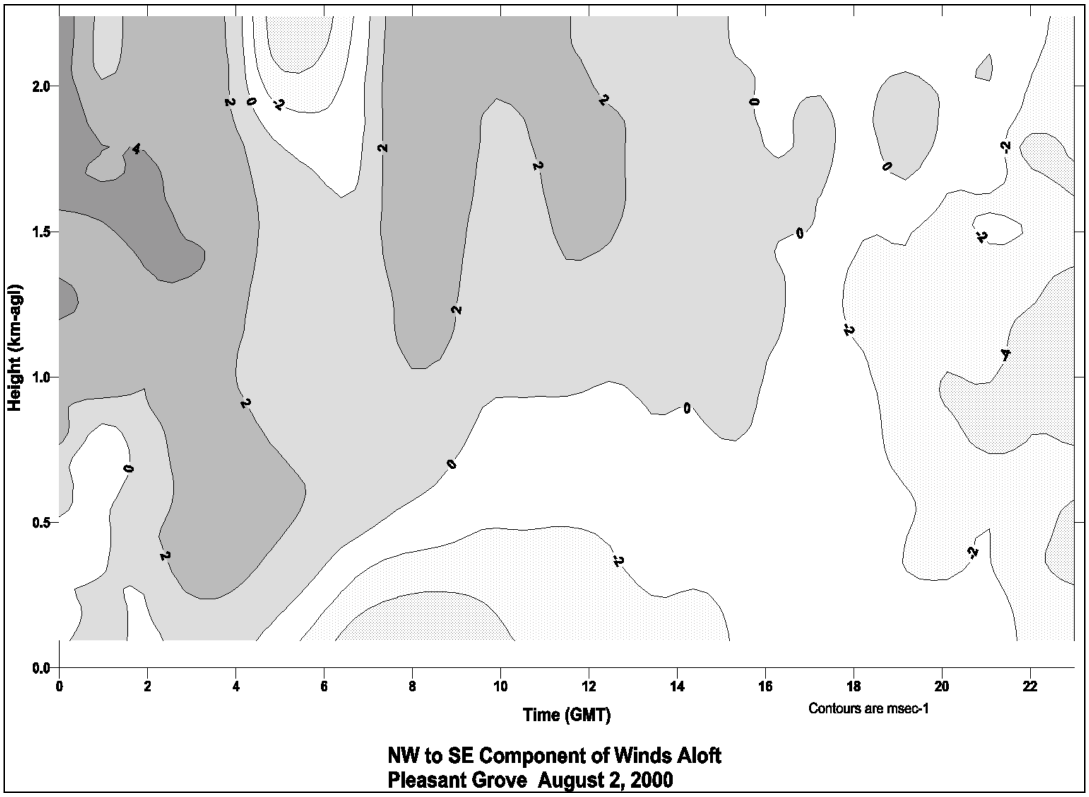
Waterford August 1, 2000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Time (GMT)
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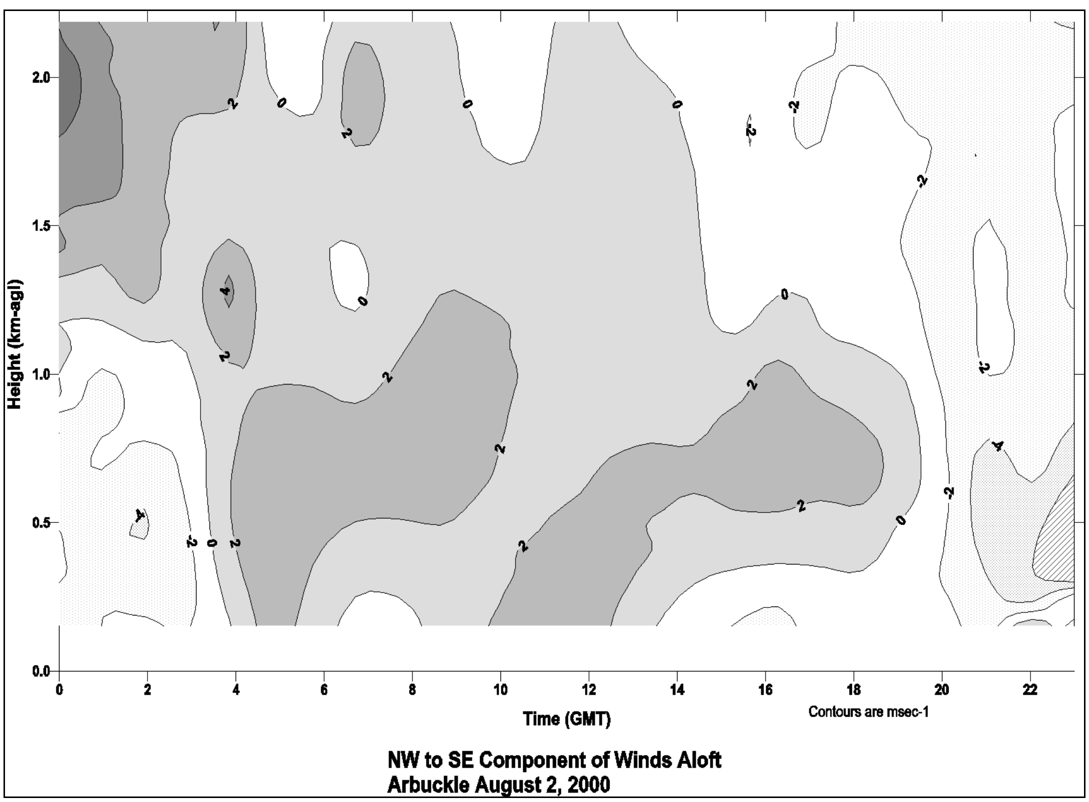
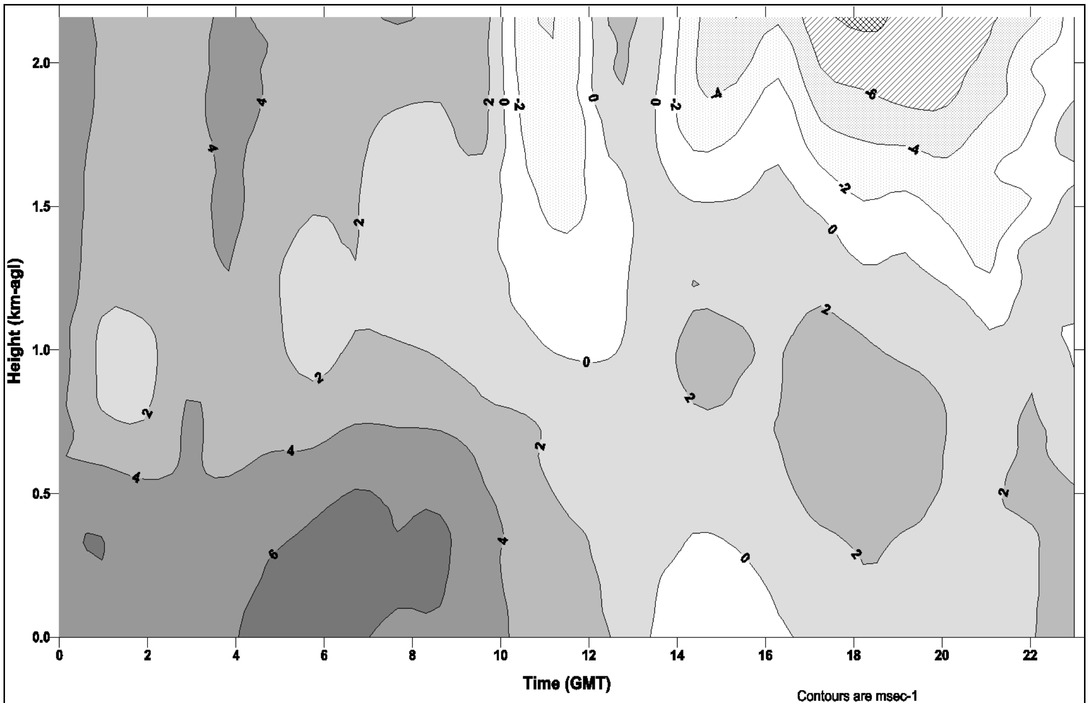
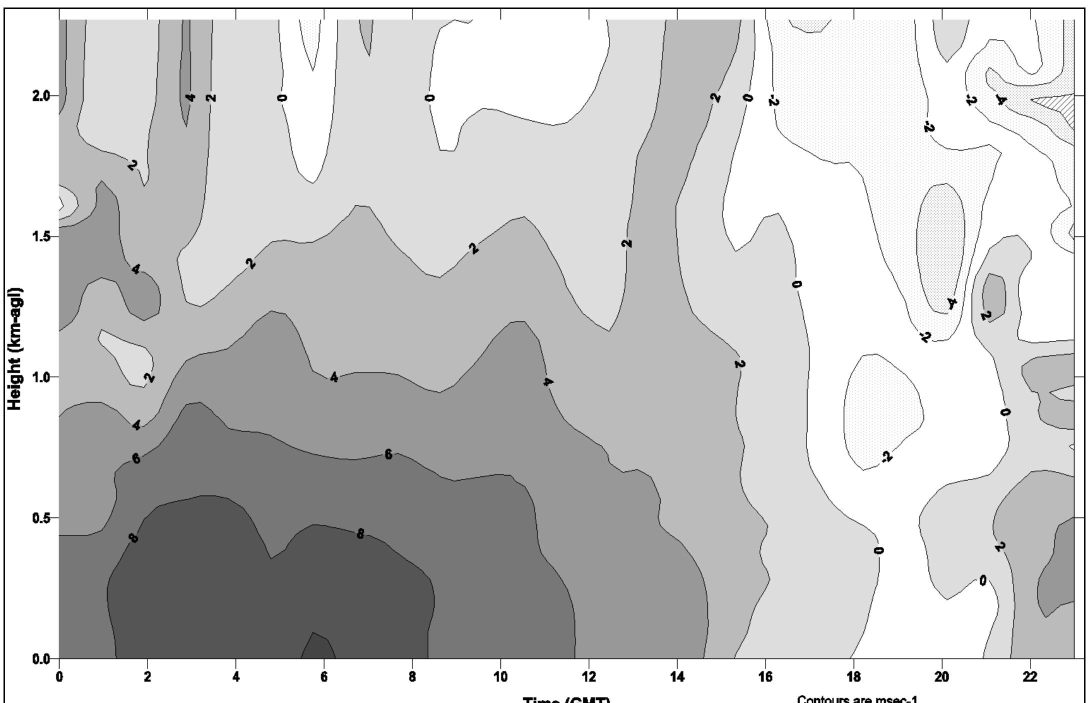
NW to SE Component of Winds Aloft
Pleasant Grove August 2, 2000

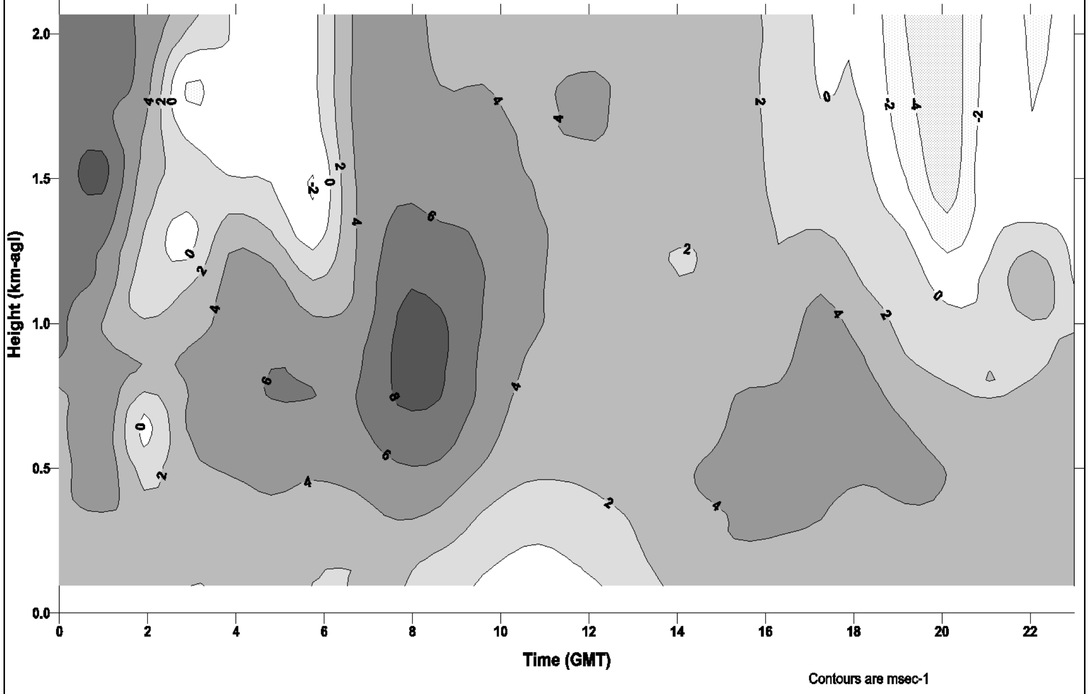

Height (km-agl)
Time (GMT)
Contours are msec-1
NW to SE Component of Winds Aloft
Arbuckle August 2, 2000



NW to SE Component of Winds Aloft
Visalia August 2, 2000



NW to SE Component of Winds Aloft
Waterford August 2, 2000



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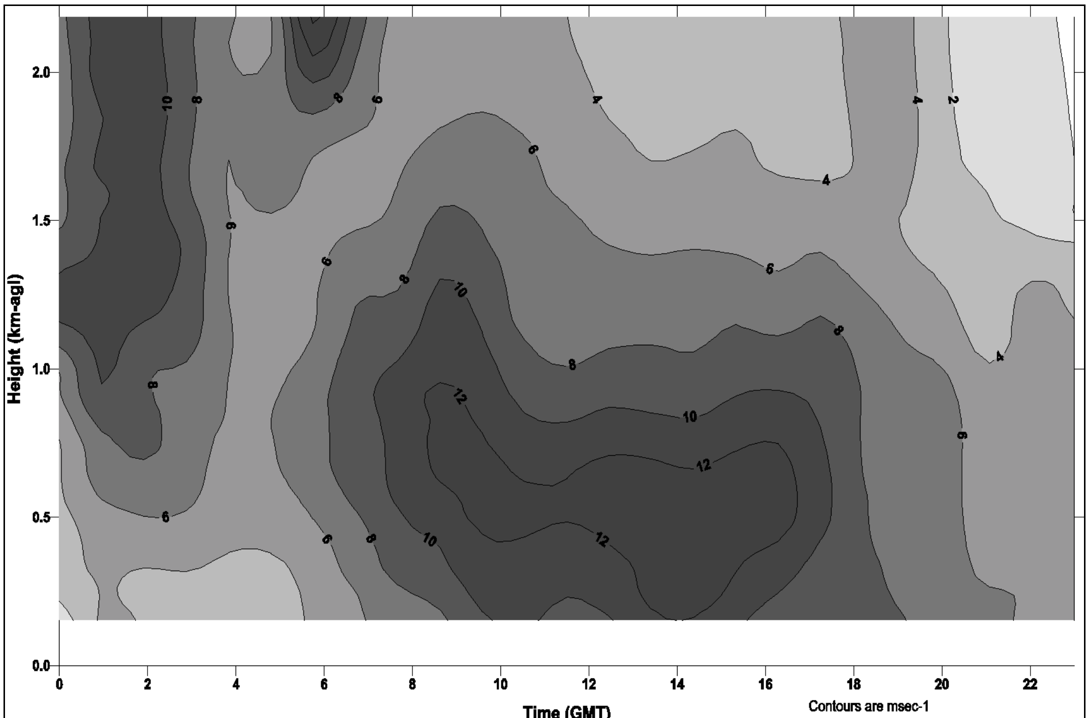

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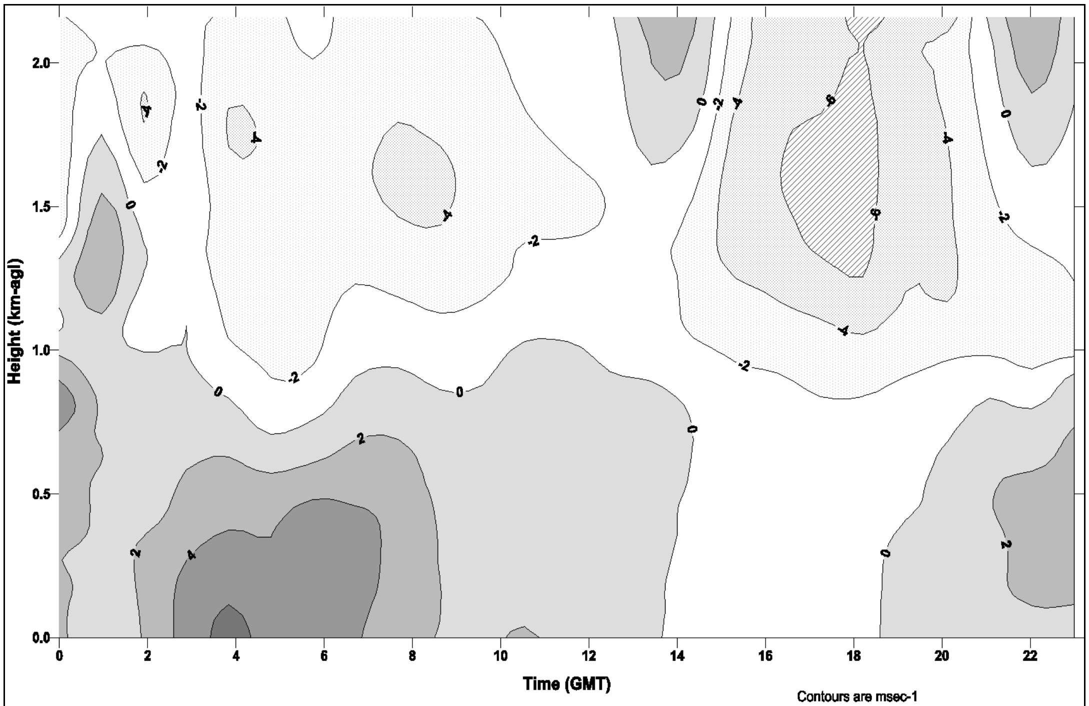

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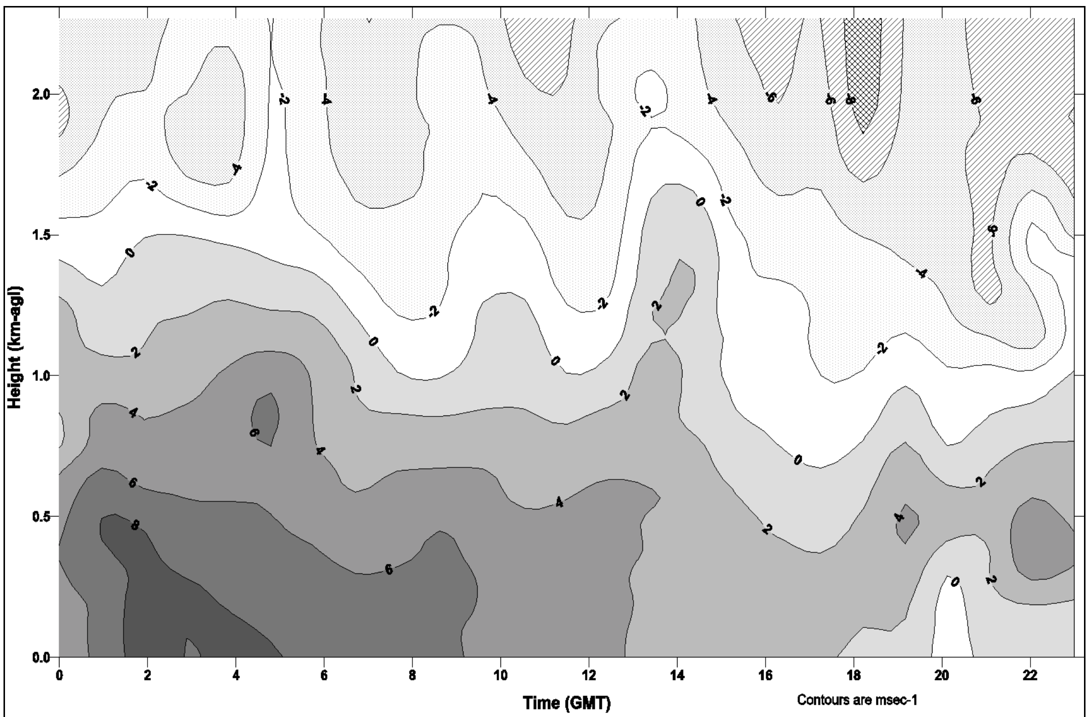

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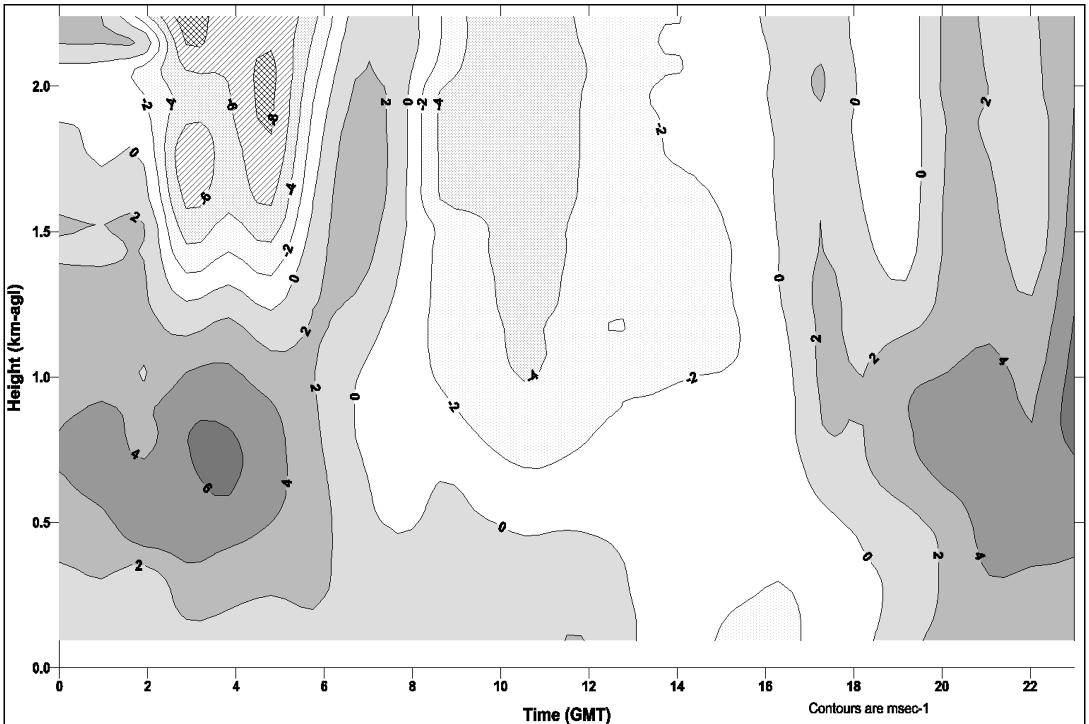
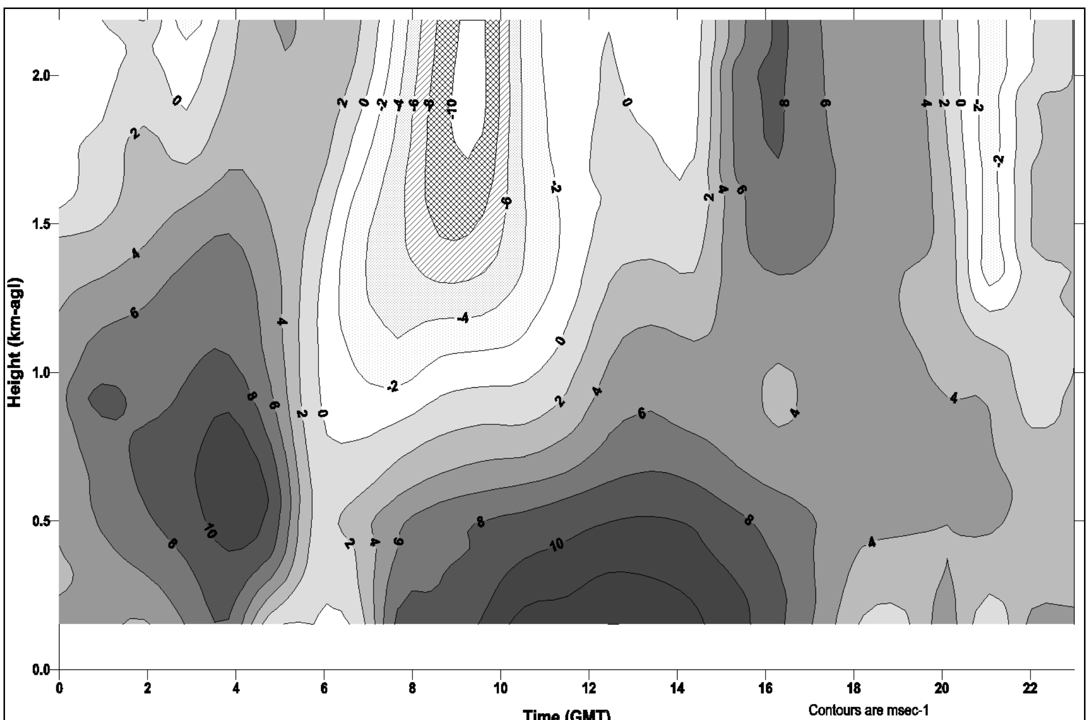
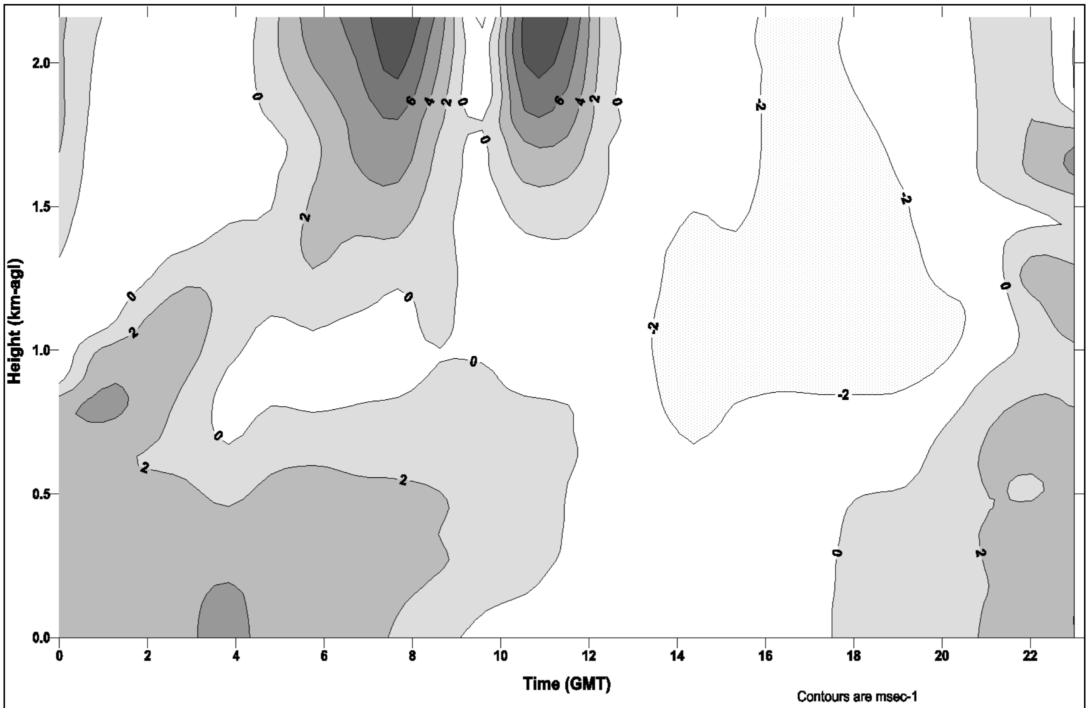
Waterford September 17, 2000



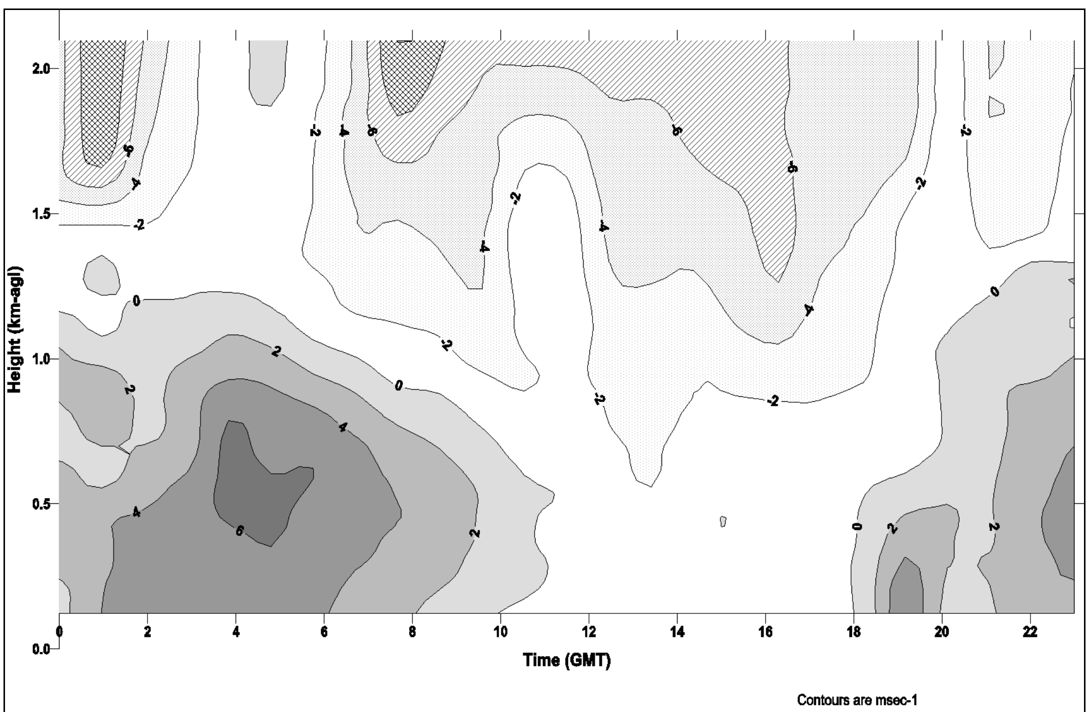
NW to SE Component of Winds Aloft
Pleasant Grove September 18, 2000



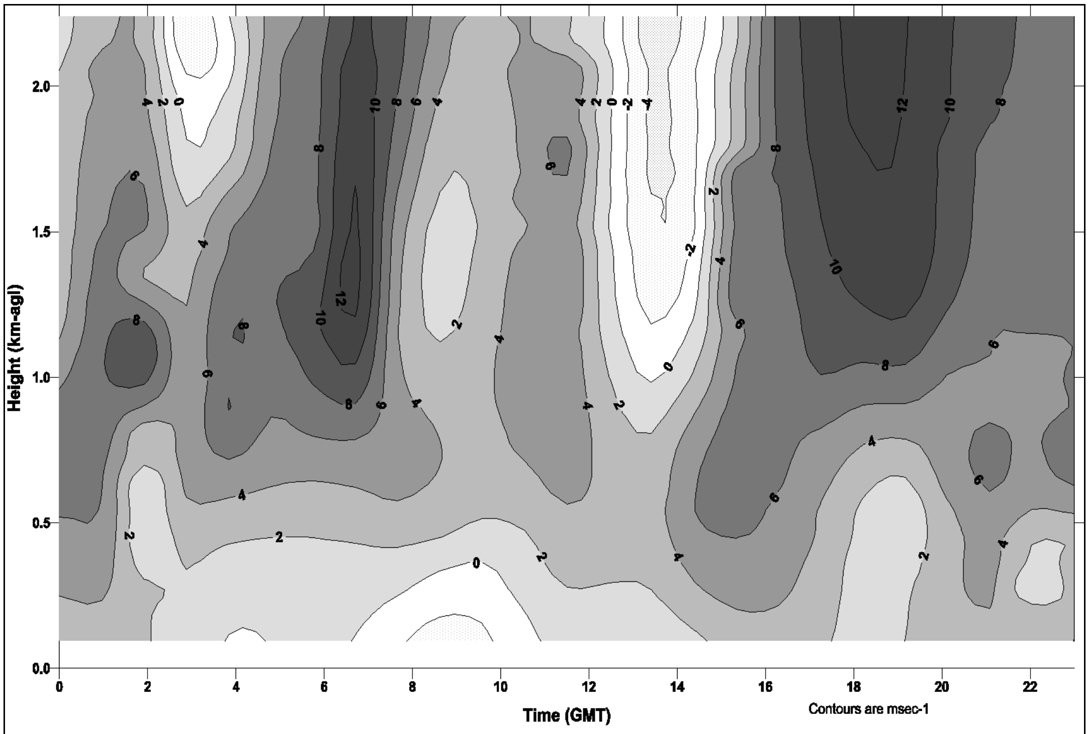
NW to SE Component of Winds Aloft
Arbuckle September 18, 2000



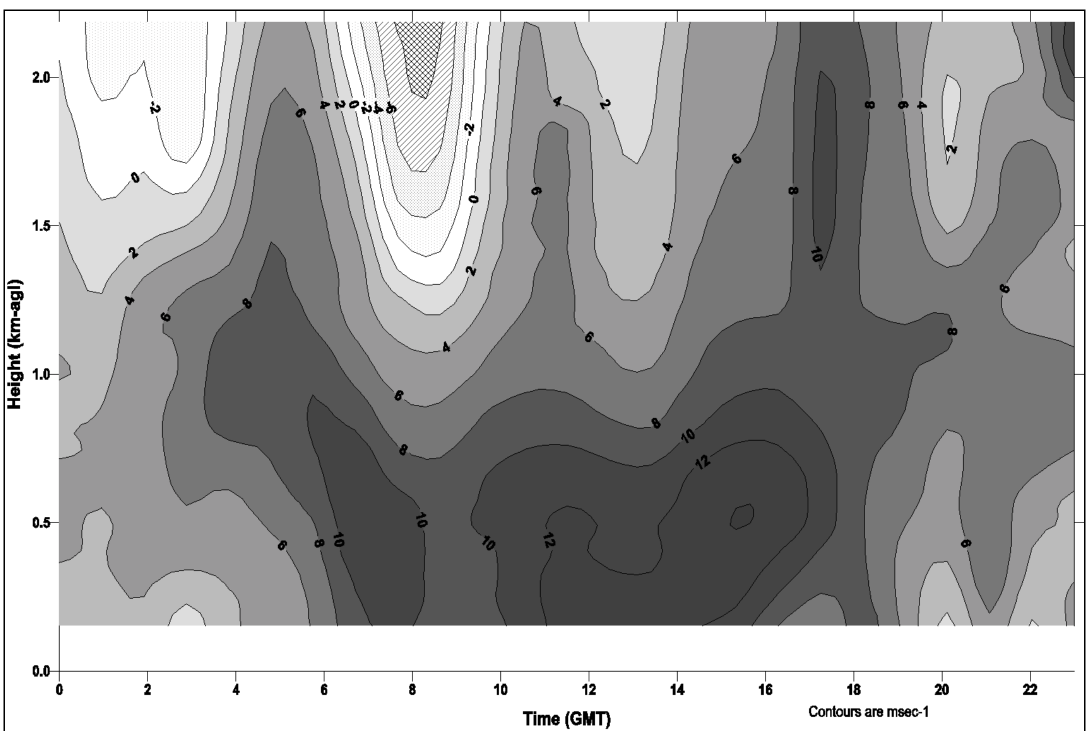
NW to SE Component of Winds Aloft
Visalia September 18, 2000



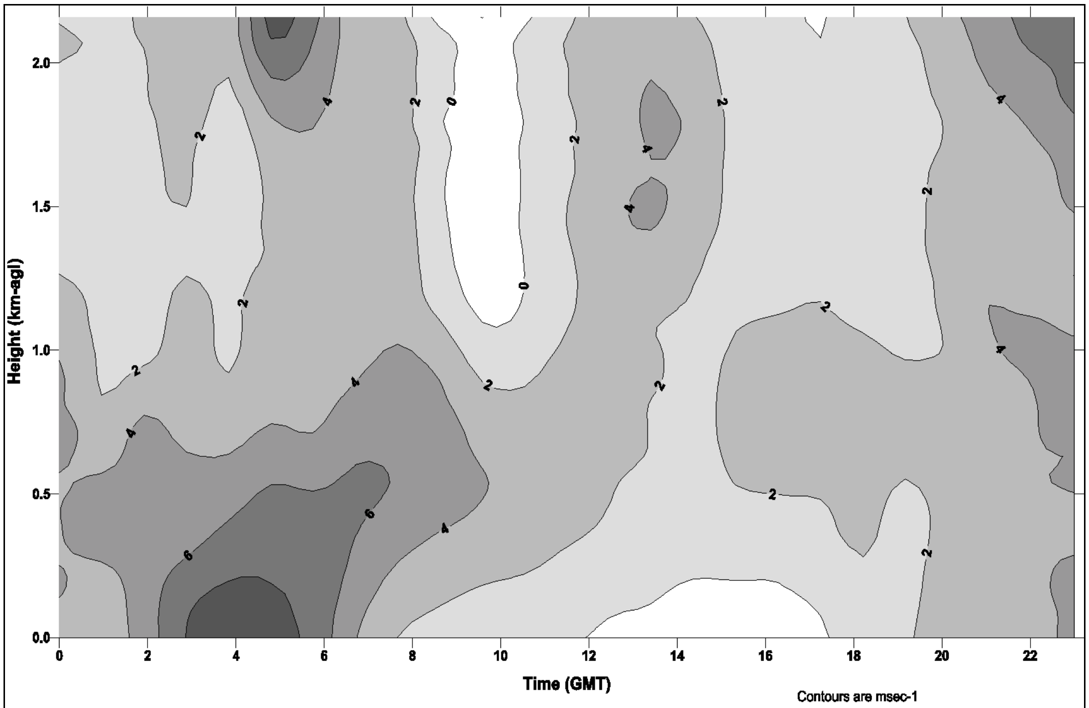
NW to SE Component of Winds Aloft
Waterford September 18, 2000



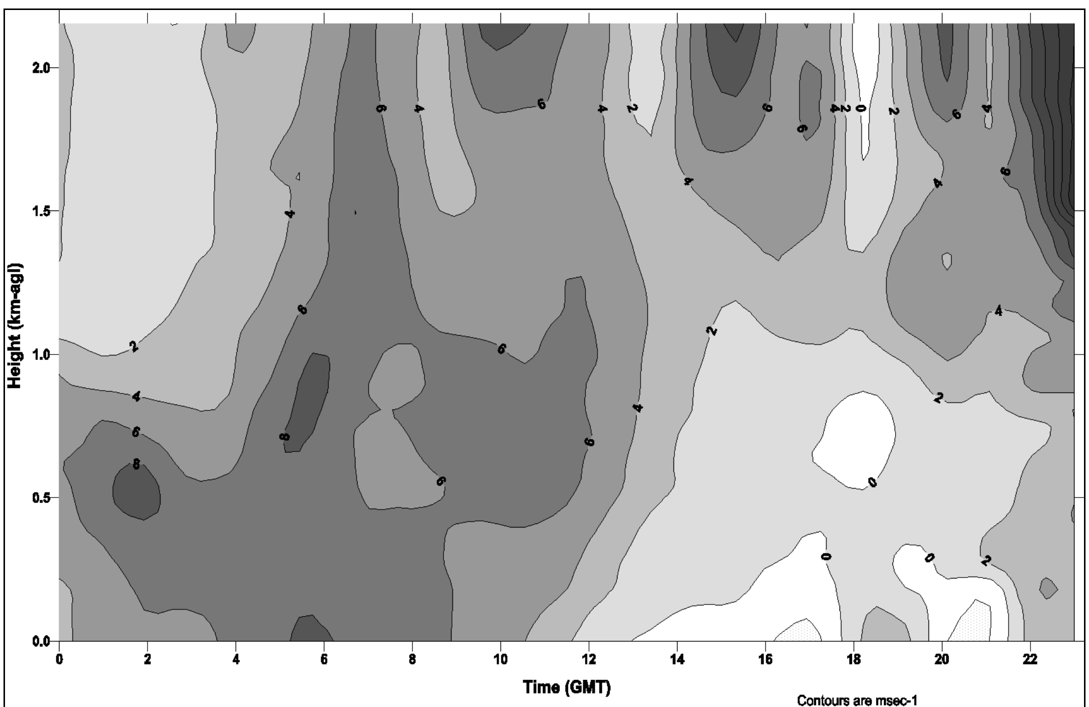
NW to SE Component of Winds Aloft
Pleasant Grove September 19, 2000



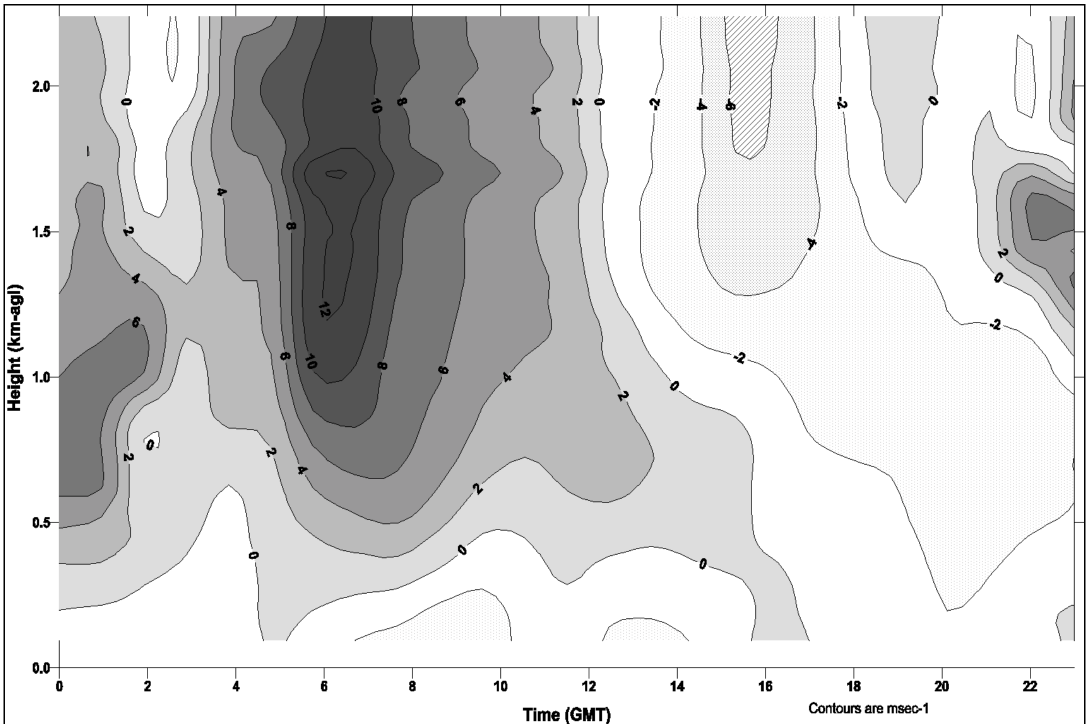
NW to SE Component of Winds Aloft
Arbuckle September 19, 2000



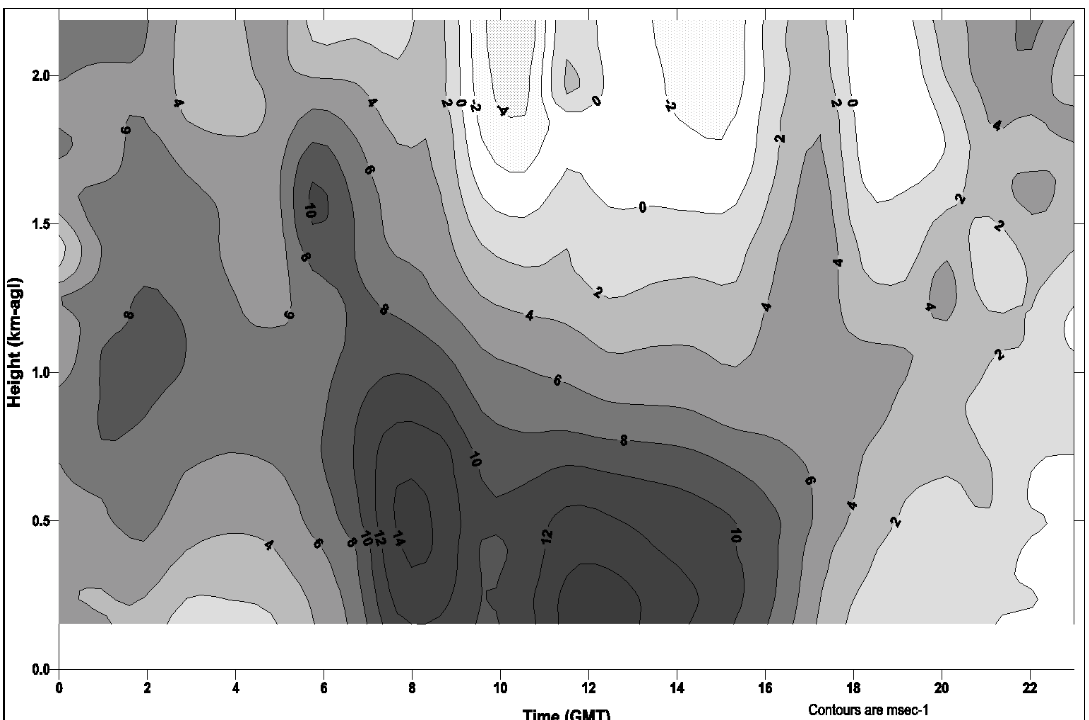
NW to SE Component of Winds Aloft
Visalia September 19, 2000



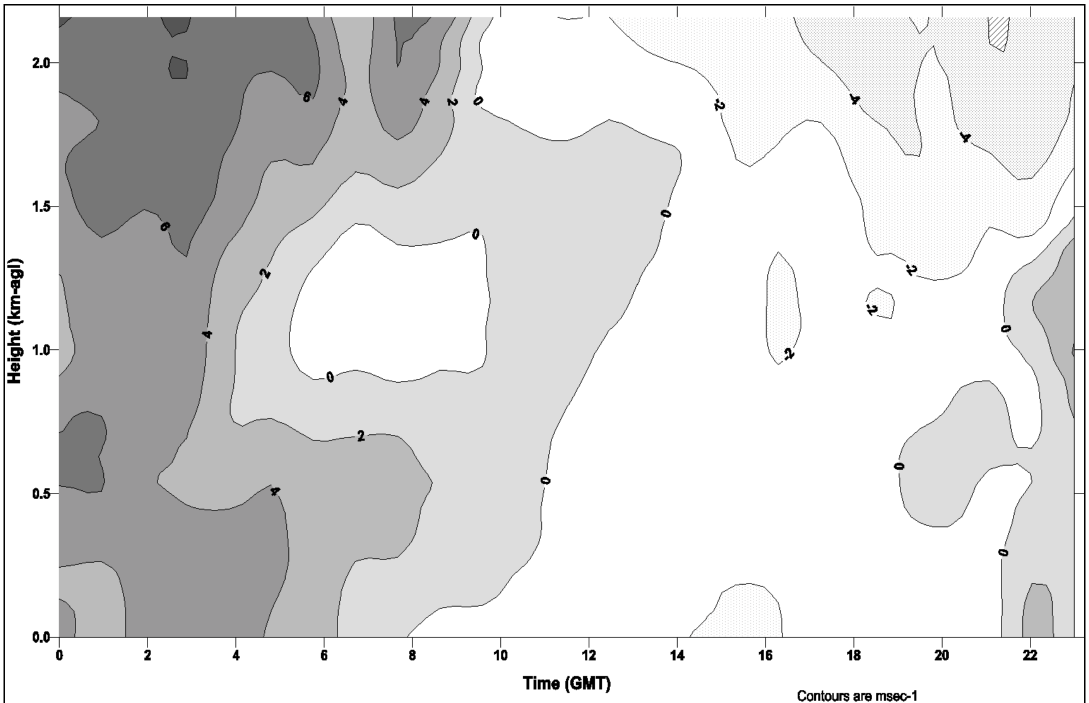
NW to SE Component of Winds Aloft
Waterford September 19, 2000



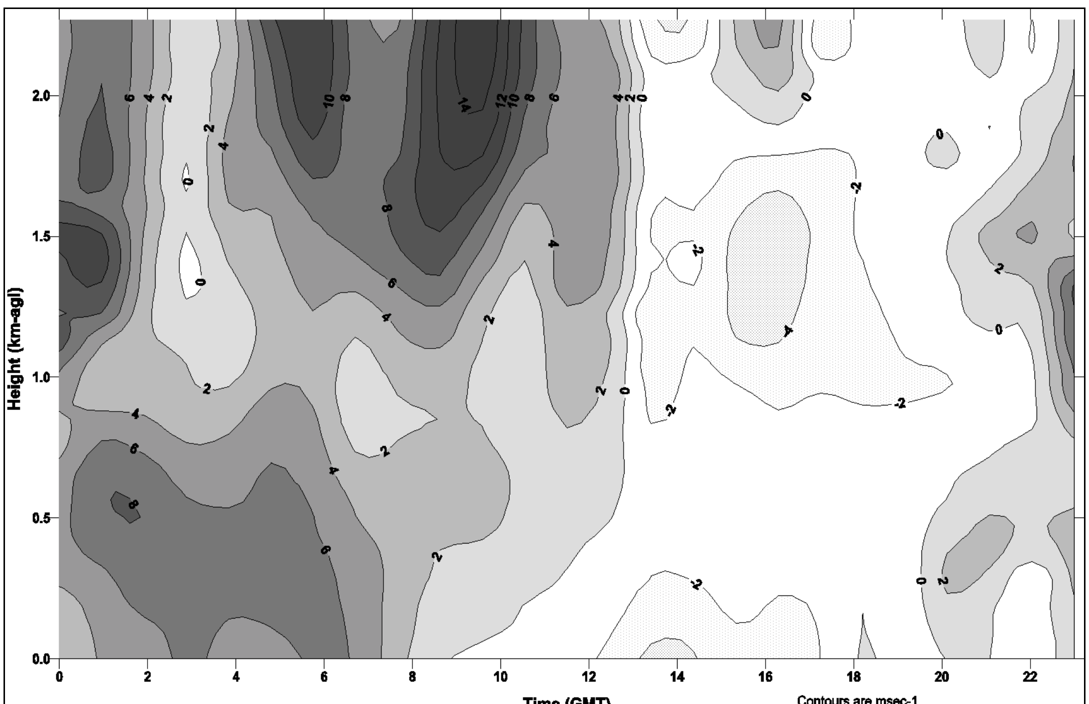
NW to SE Component of Winds Aloft
Pleasant Grove September 20, 2000



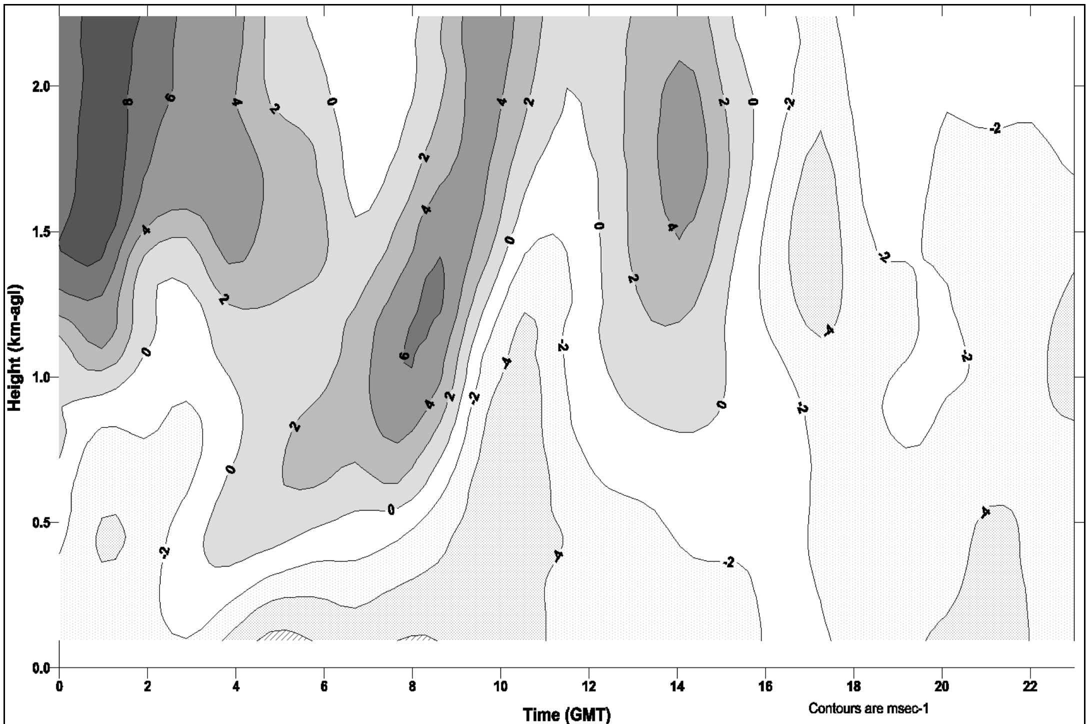
NW to SE Component of Winds Aloft
Arbuckle September 20, 2000



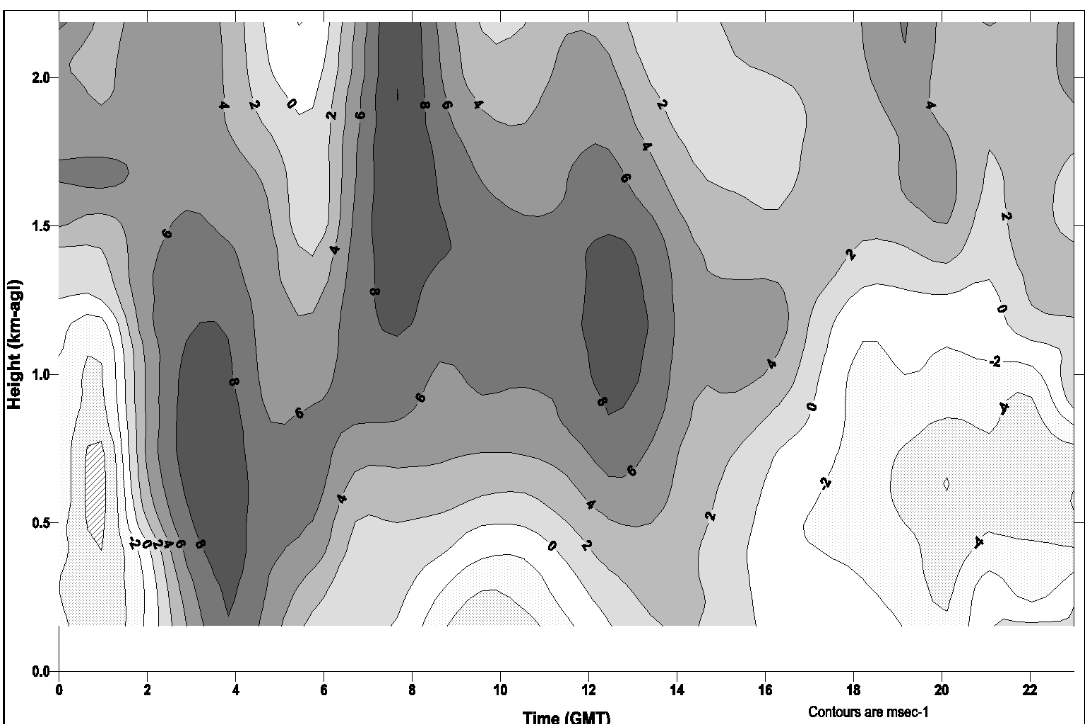
NW to SE Component of Winds Aloft
Visalia September 20, 2000



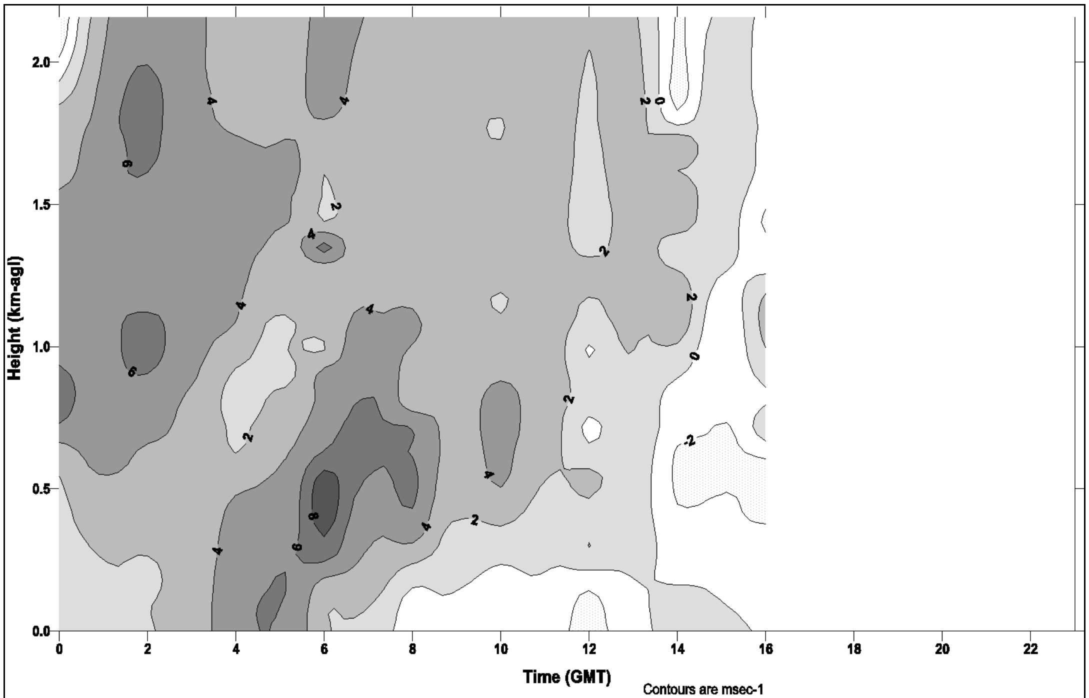
NW to SE Component of Winds Aloft
Waterford September 20, 2000



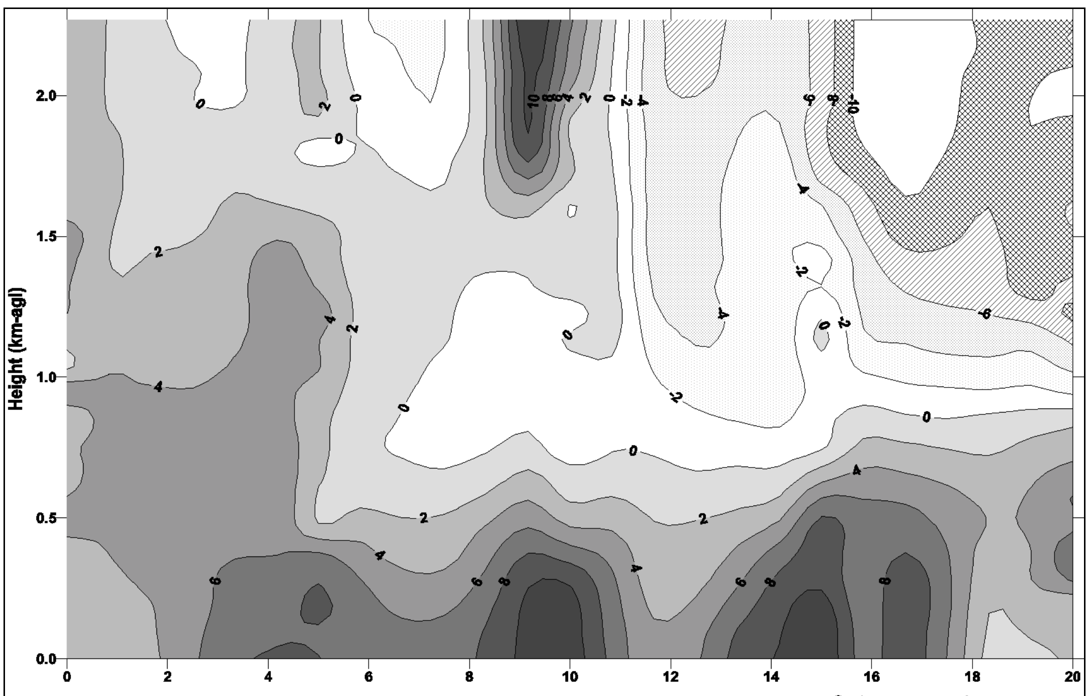
NW to SE Component of Winds Aloft
Pleasant Grove September 21, 2000



NW to SE Component of Winds Aloft
Arbuckle September 21, 2000



NW to SE Component of Winds Aloft
Visalia September 21, 2000



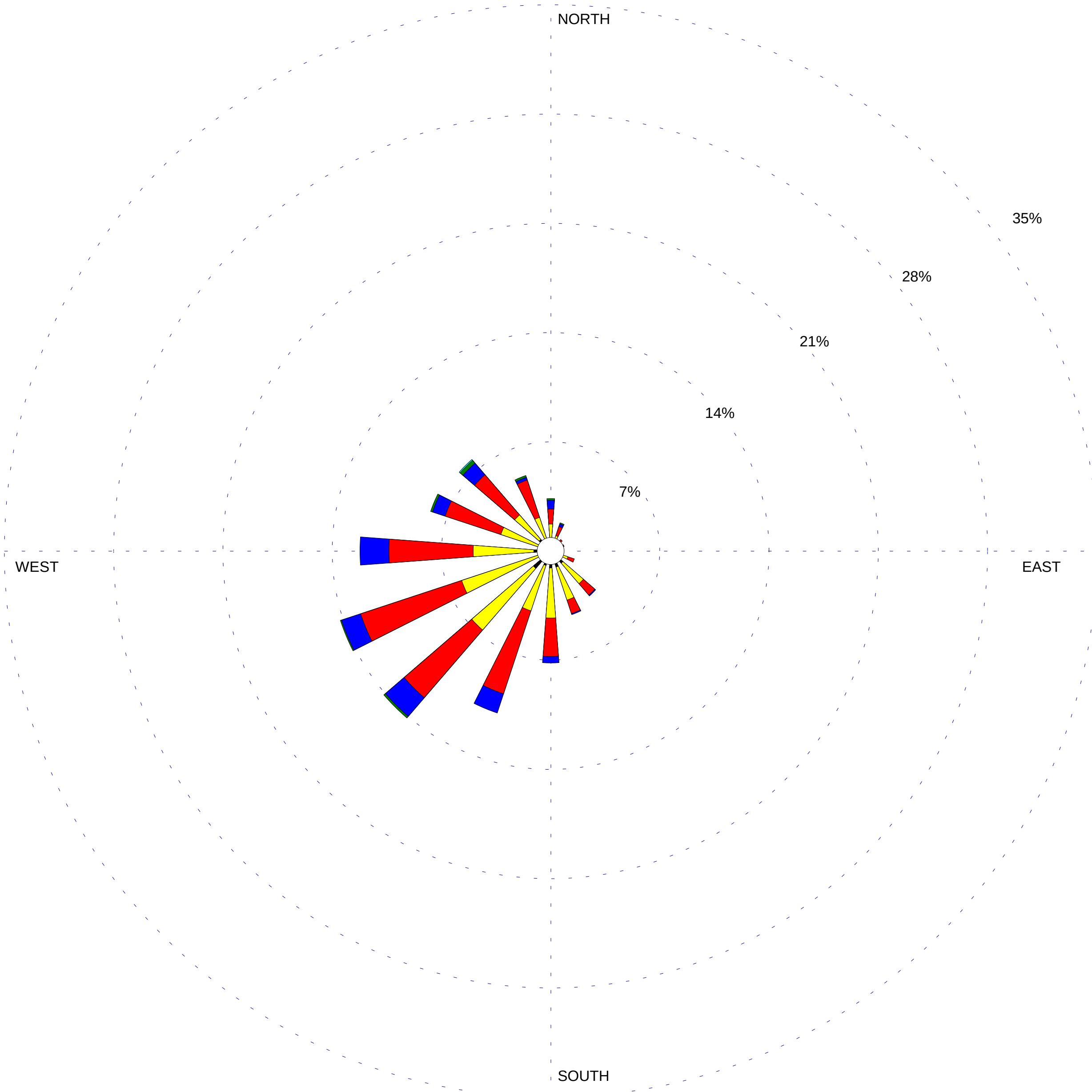
NW to SE Component of Winds Aloft
Waterford September 21, 2000

APPENDIX C

Oakland 500 mb Wind Roses

CCOS Analysis 01-2

Station #OAK 500mb June-September 1986-2000

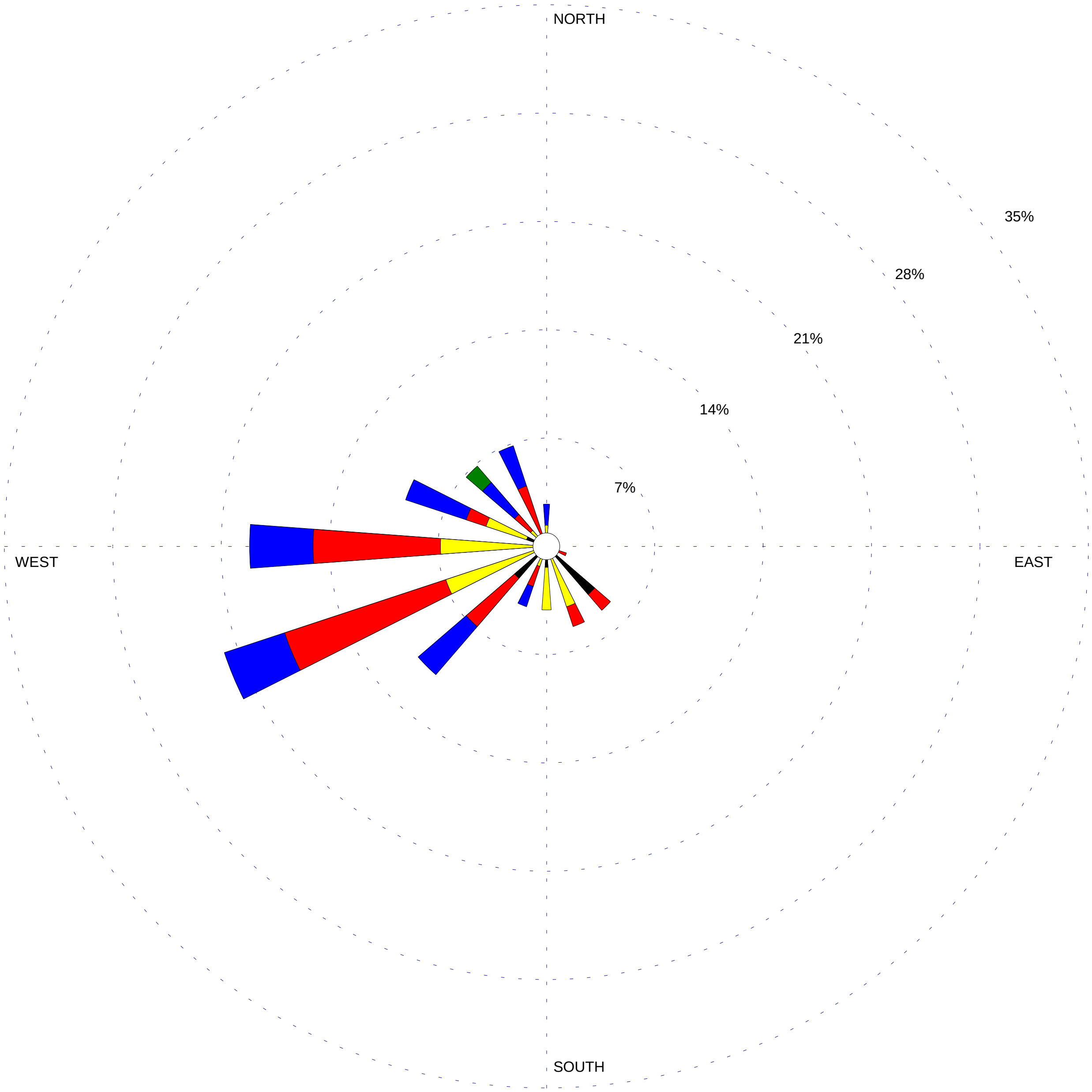


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **5.82 m/s**	CALM WINDS **2.70%**	
	Direction (blowing from)	**1986 1987 1988 1989 1990 2000 1999 1998 1997 1996 1 - 30Sep Jun 1991 1992 1993 1994 1995 Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1986

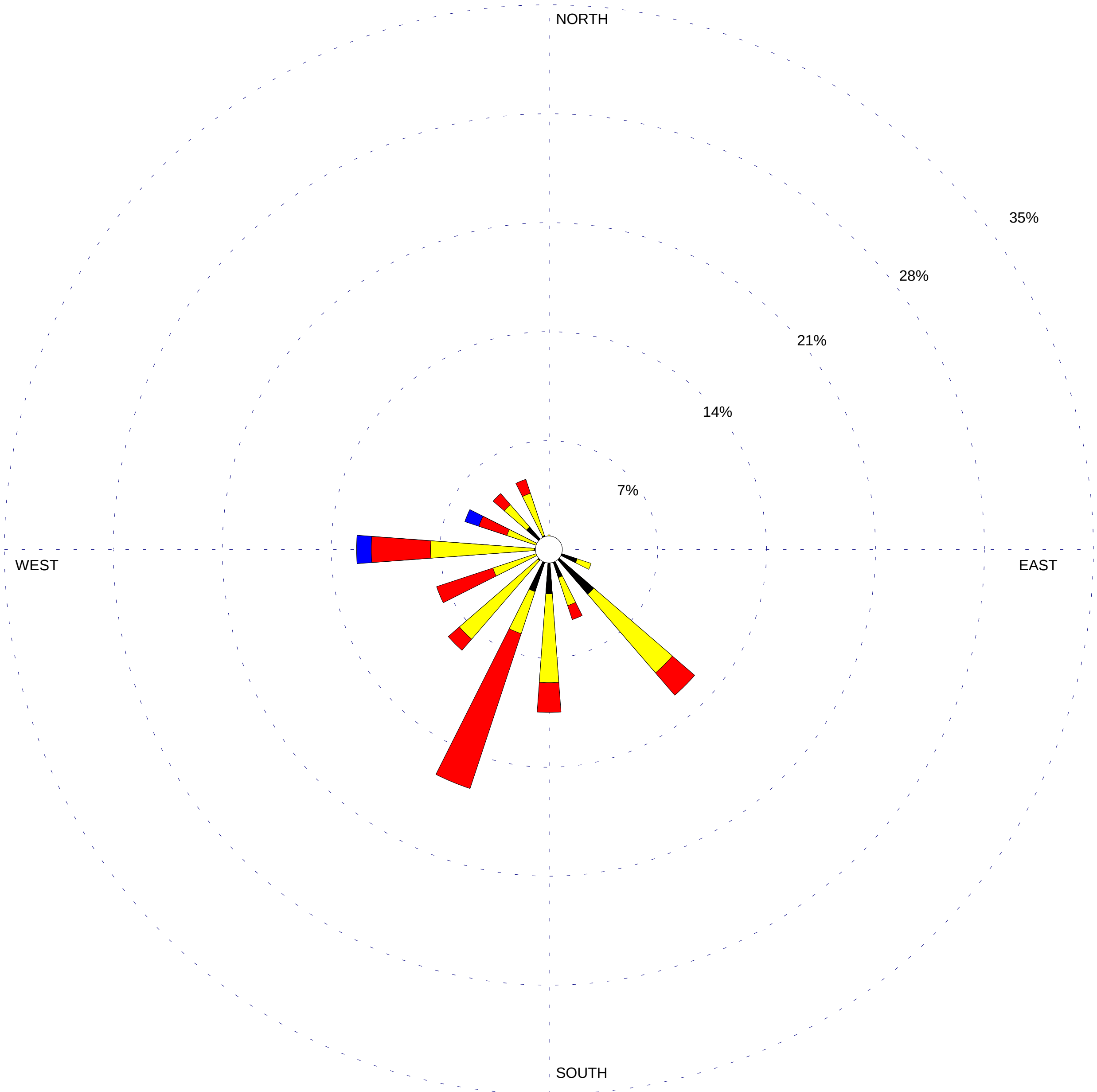


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **7.25 m/s**	CALM WINDS **1.37%**	
	Direction (blowing from)	**1986 Jun 1 - Sep 30 Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1987

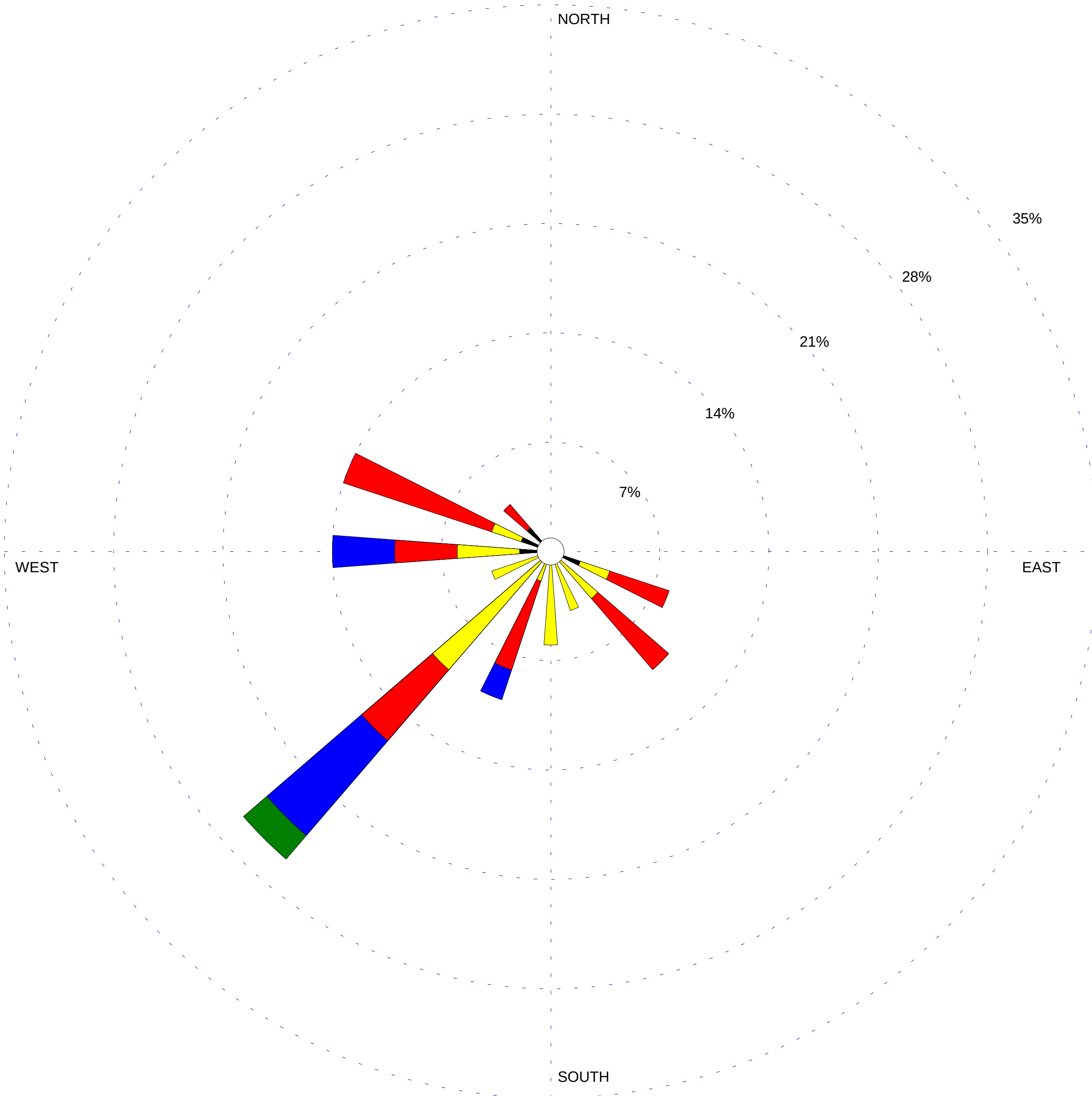


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
10.00 - 15.00 5.00 - 10.00	AVG. WIND SPEED **4.57 m/s**	CALM WINDS **8.57%**	
2.50 - 5.00 1.00 - 2.50	**Direction (blowing from)**	**1987** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1988

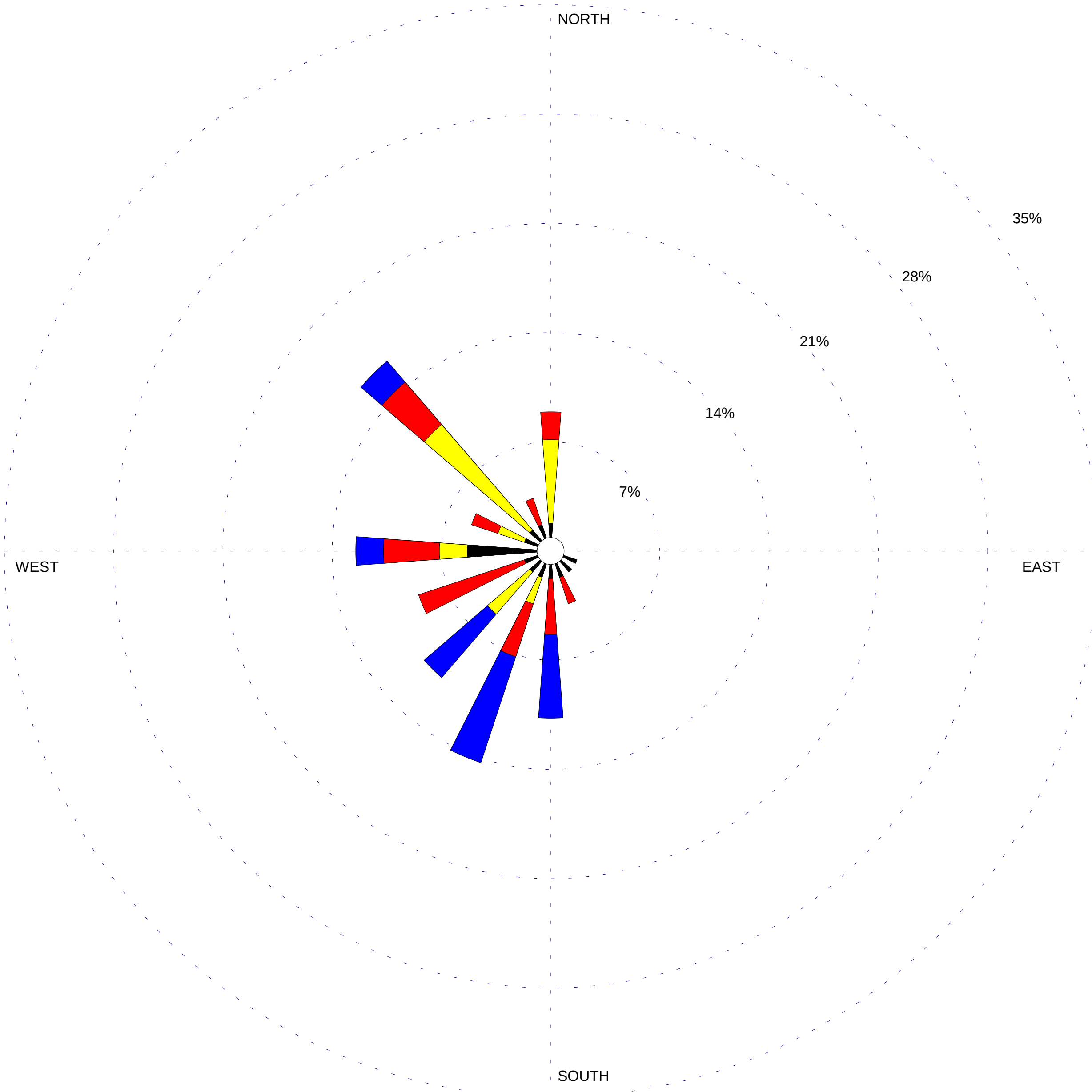


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **6.15 m/s**	CALM WINDS **0.00%**	
	Direction (blowing from)	**1988** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1989

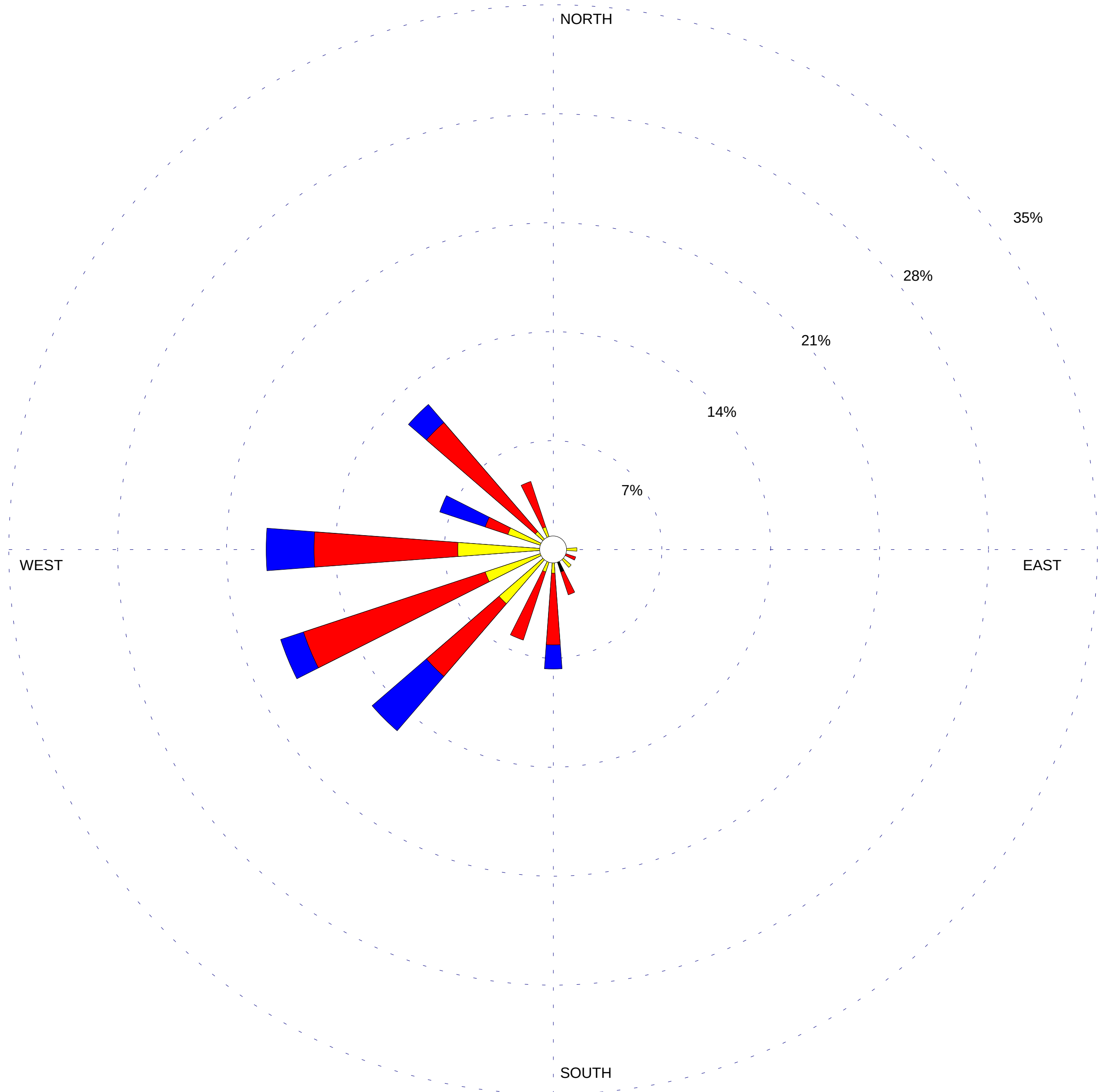


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
15.00 - 20.00			
10.00 - 15.00	AVG. WIND SPEED **5.99 m/s**	CALM WINDS **1.79%**	
5.00 - 10.00			
2.50 - 5.00	**Direction (blowing from)**	**1989 Jun 1 - Sep 30 Midnight - 11 PM**	
1.00 - 2.50			

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1990



Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
10.00 - 15.00 5.00 - 10.00	AVG. WIND SPEED **6.90 m/s**	CALM WINDS **1.54%**	
2.50 - 5.00 1.00 - 2.50	**Direction (blowing from)**	**1990** **Jun 1 - Sep 30** **Midnight - 11 PM**	

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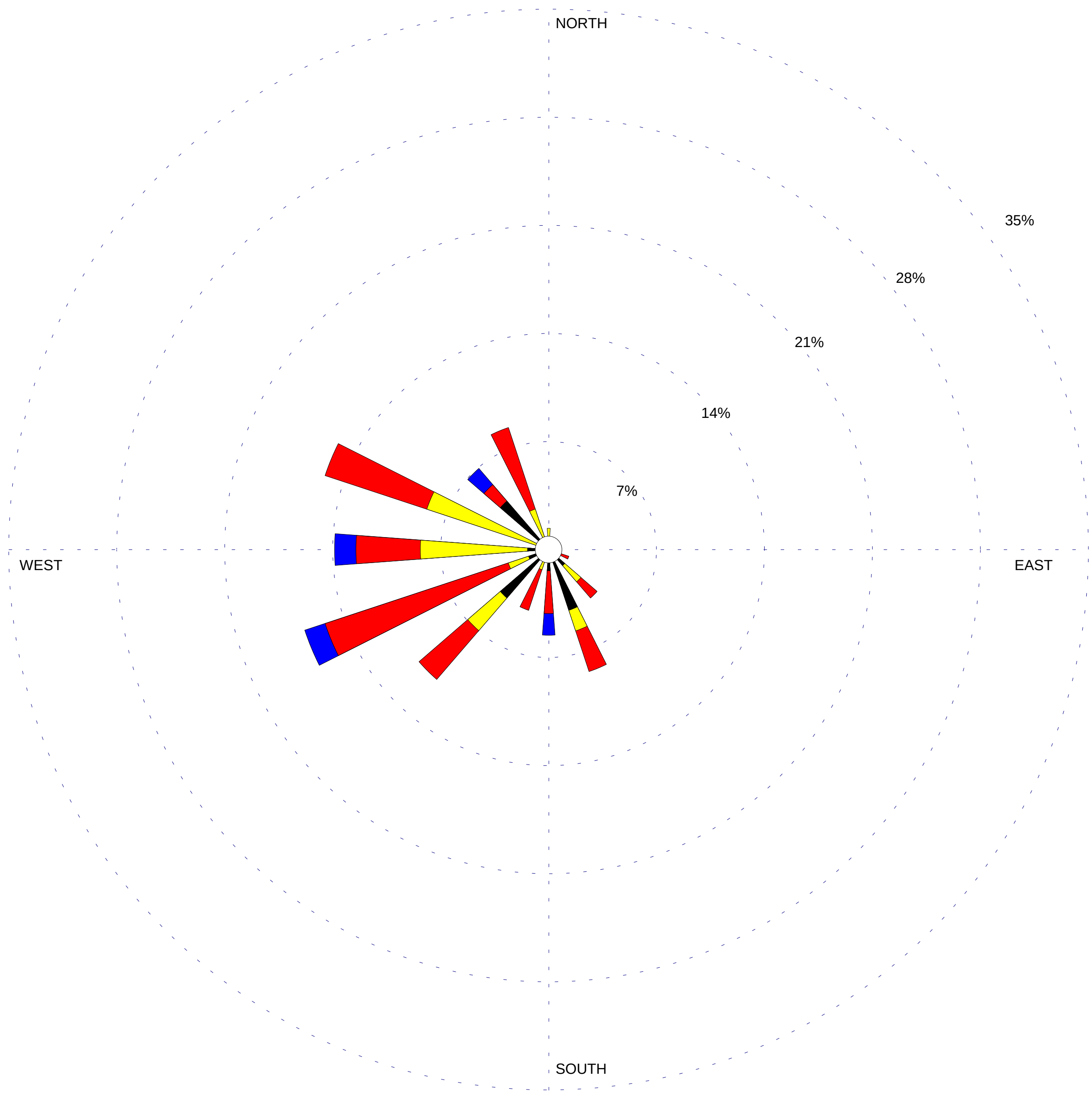
CCOS Analysis 01-2

Station #Oakland 500mb June-September 1991

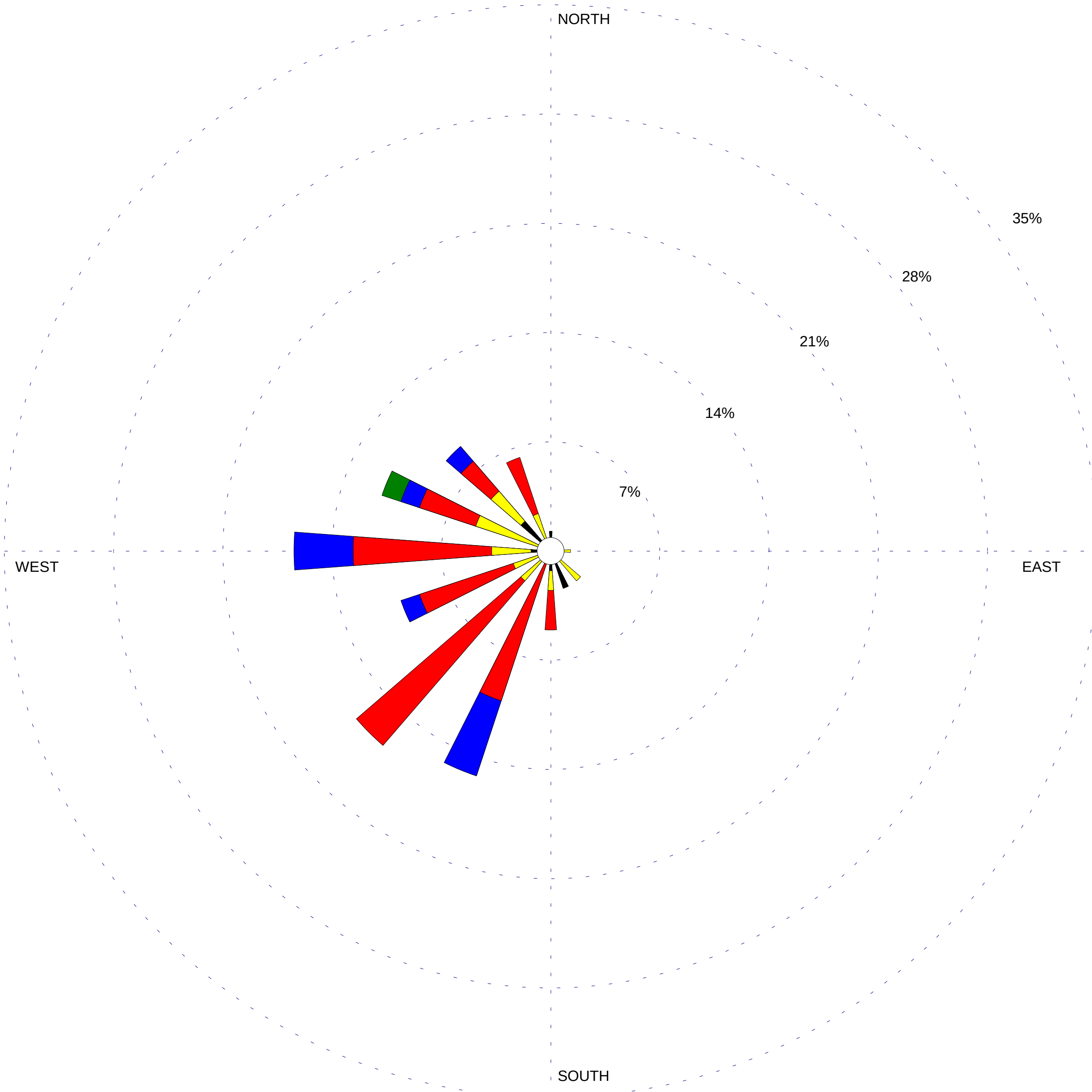


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **5.37 m/s**	CALM WINDS **2.78%**	
	Direction (blowing from)	**1991** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1992



Wind Speed (m/s)

> 20.00
15.00 - 20.00
10.00 - 15.00
5.00 - 10.00
2.50 - 5.00
1.00 - 2.50

DATE
10/25/01

T&B Systems
TB Systems

DISPLAY
Wind Speed

Units:
m/s

COMMENTS

AVG. WIND SPEED
6.71 m/s

CALM WINDS
2.53%

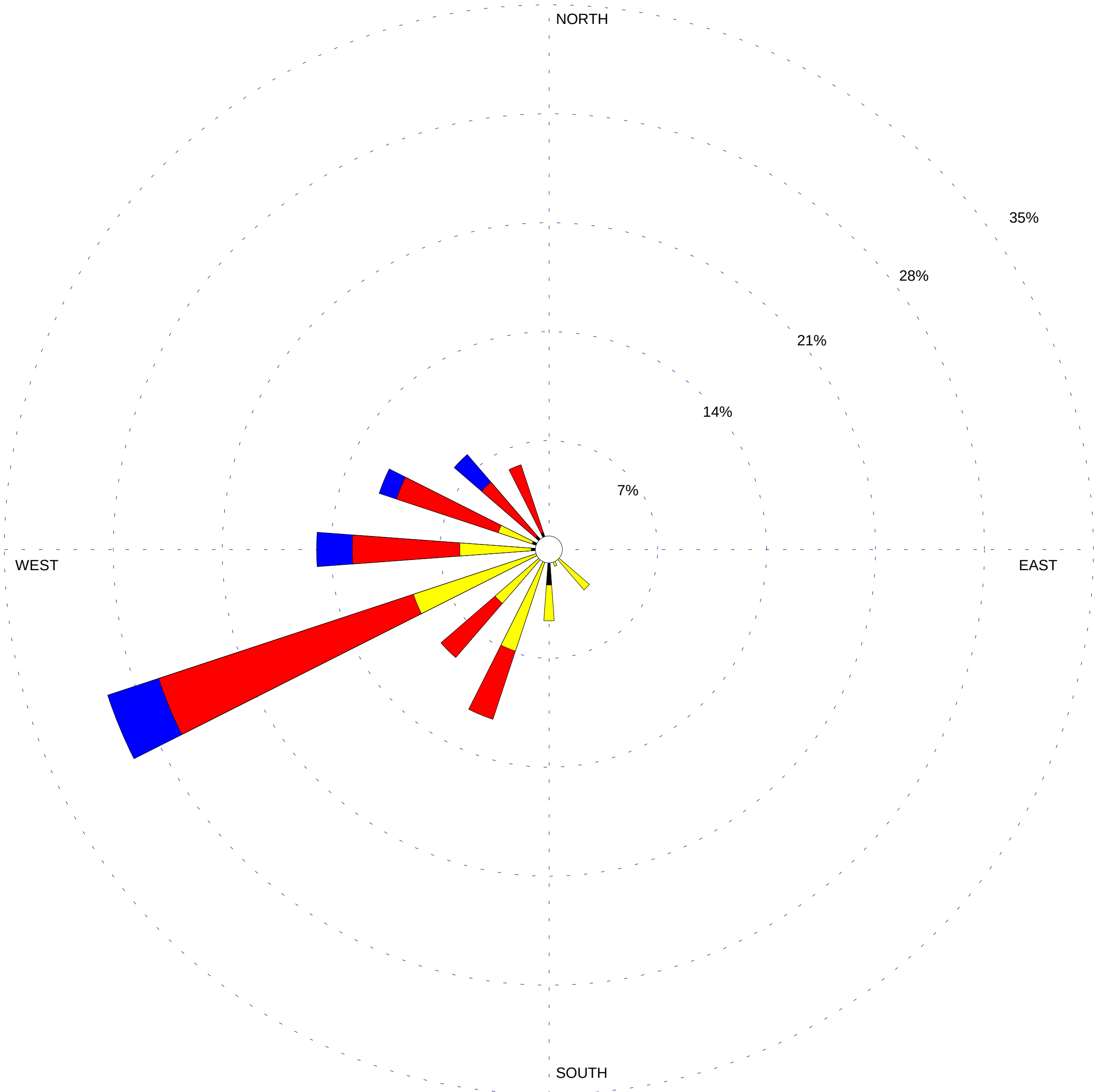
Direction (blowing from)

1992
Jun 1 - Sep 30
Midnight - 11 PM

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1993

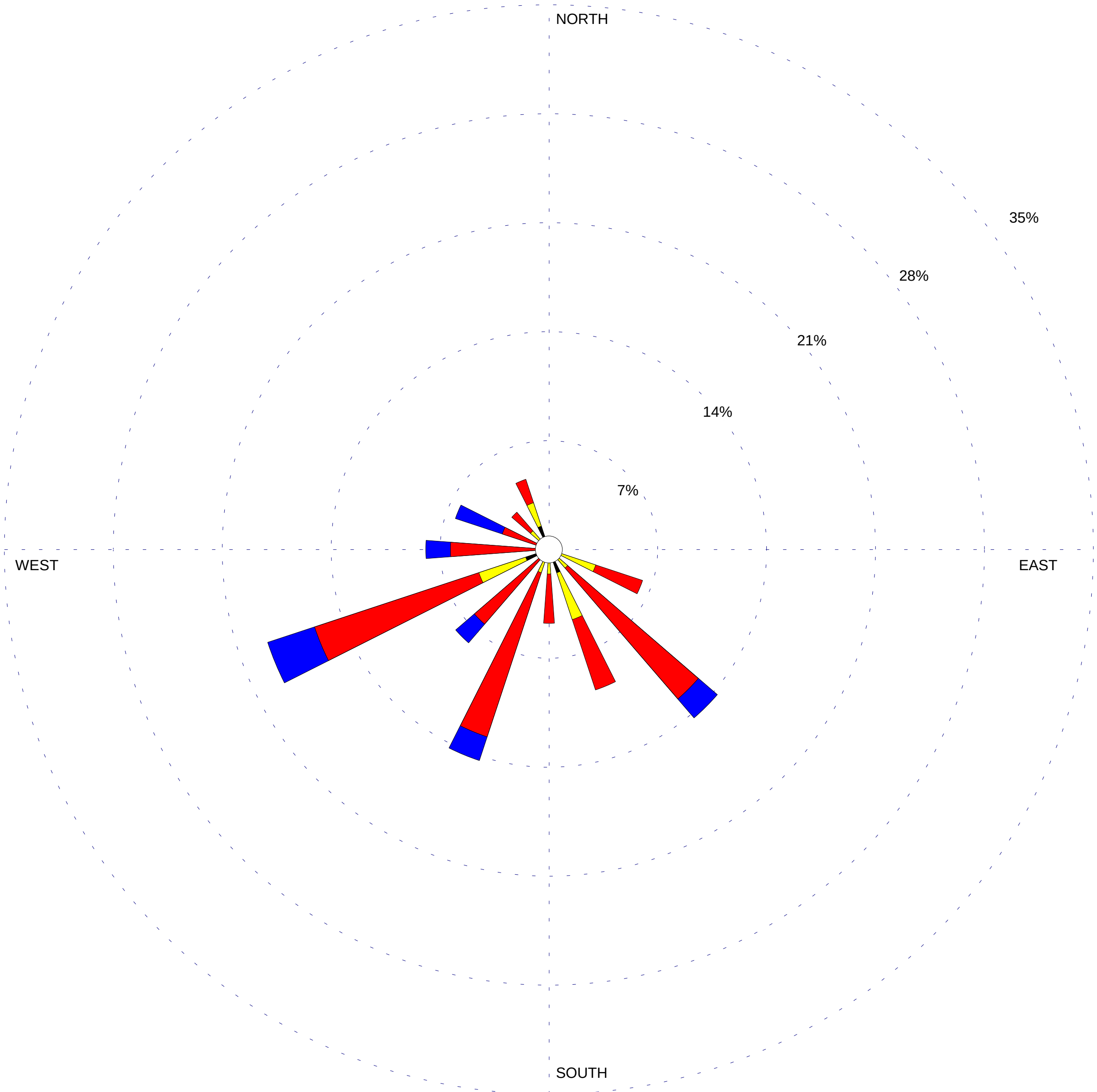


Wind Speed (m/s)		DATE	T&B Systems
> 20.00		**10/25/01**	**TB Systems**
15.00 - 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
10.00 - 15.00	AVG. WIND SPEED **6.22 m/s**	CALM WINDS **0.00%**	
5.00 - 10.00			
2.50 - 5.00	**Direction (blowing from)**	**1993** **Jun 1 - Sep 30** **Midnight - 11 PM**	
1.00 - 2.50			

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1994

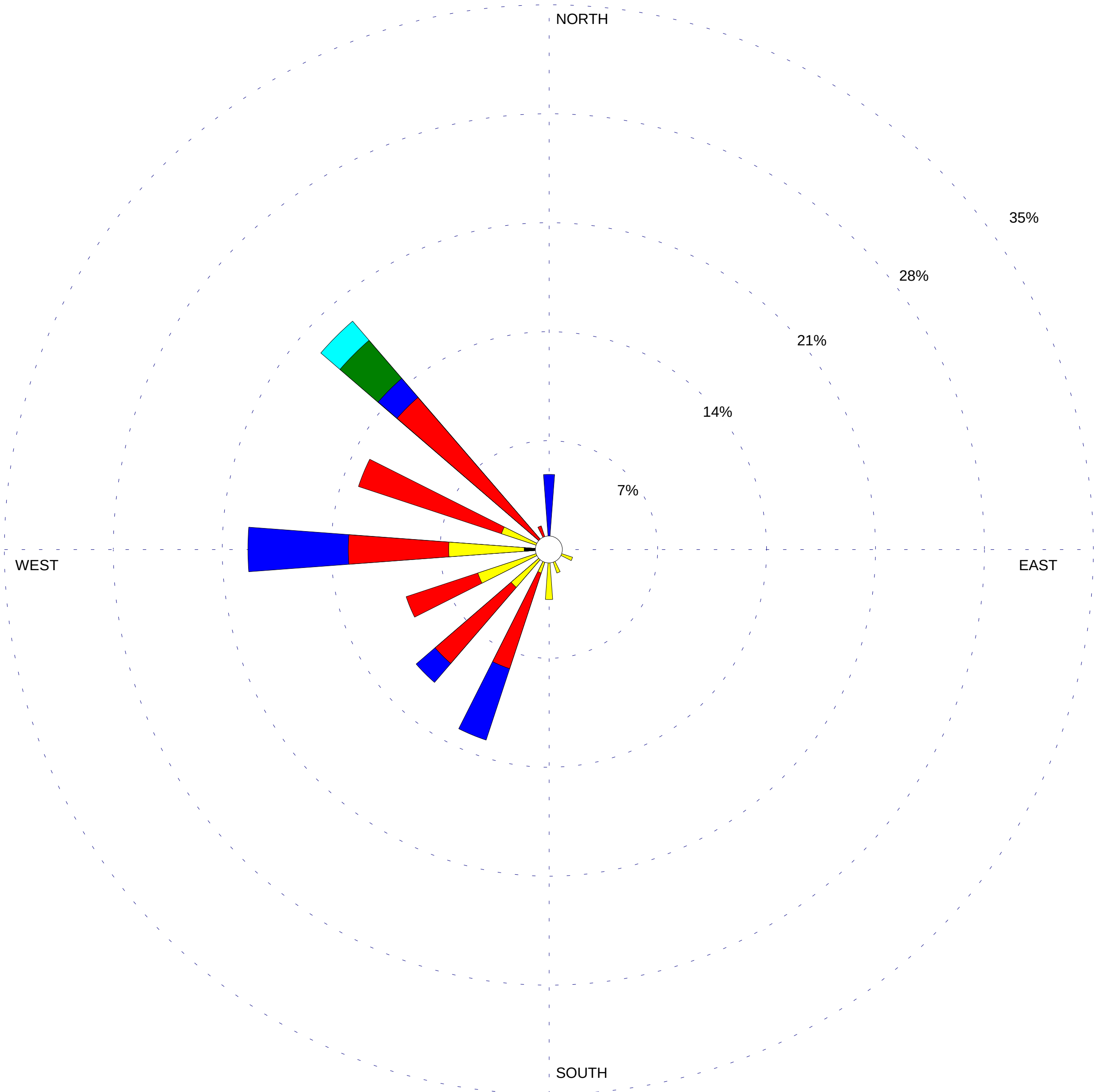


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **7.03 m/s**	CALM WINDS **1.59%**	
	Direction (blowing from)	**1994** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1995

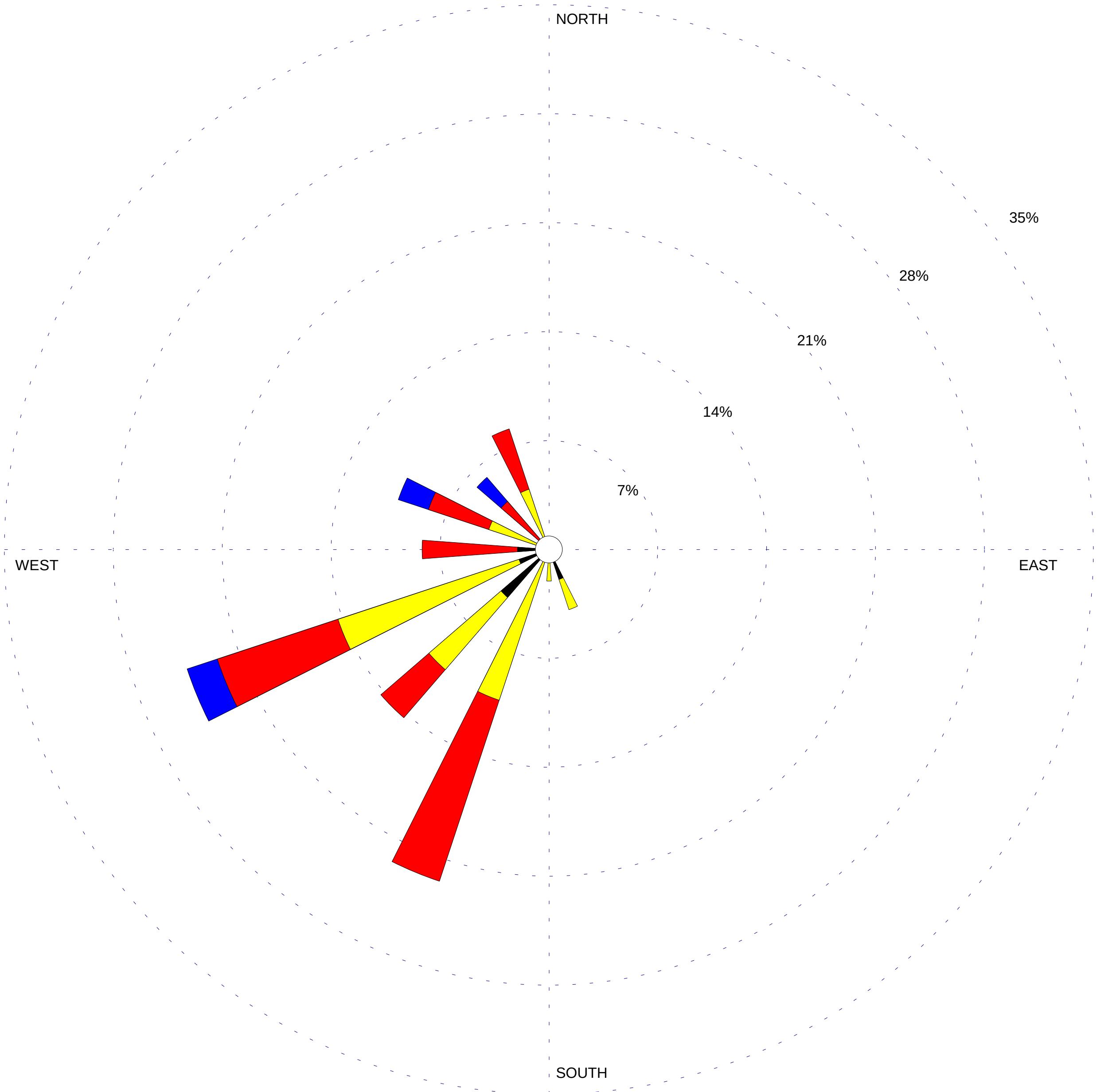


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **8.17 m/s**	CALM WINDS **1.61%**	
	Direction (blowing from)	**1995** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1996

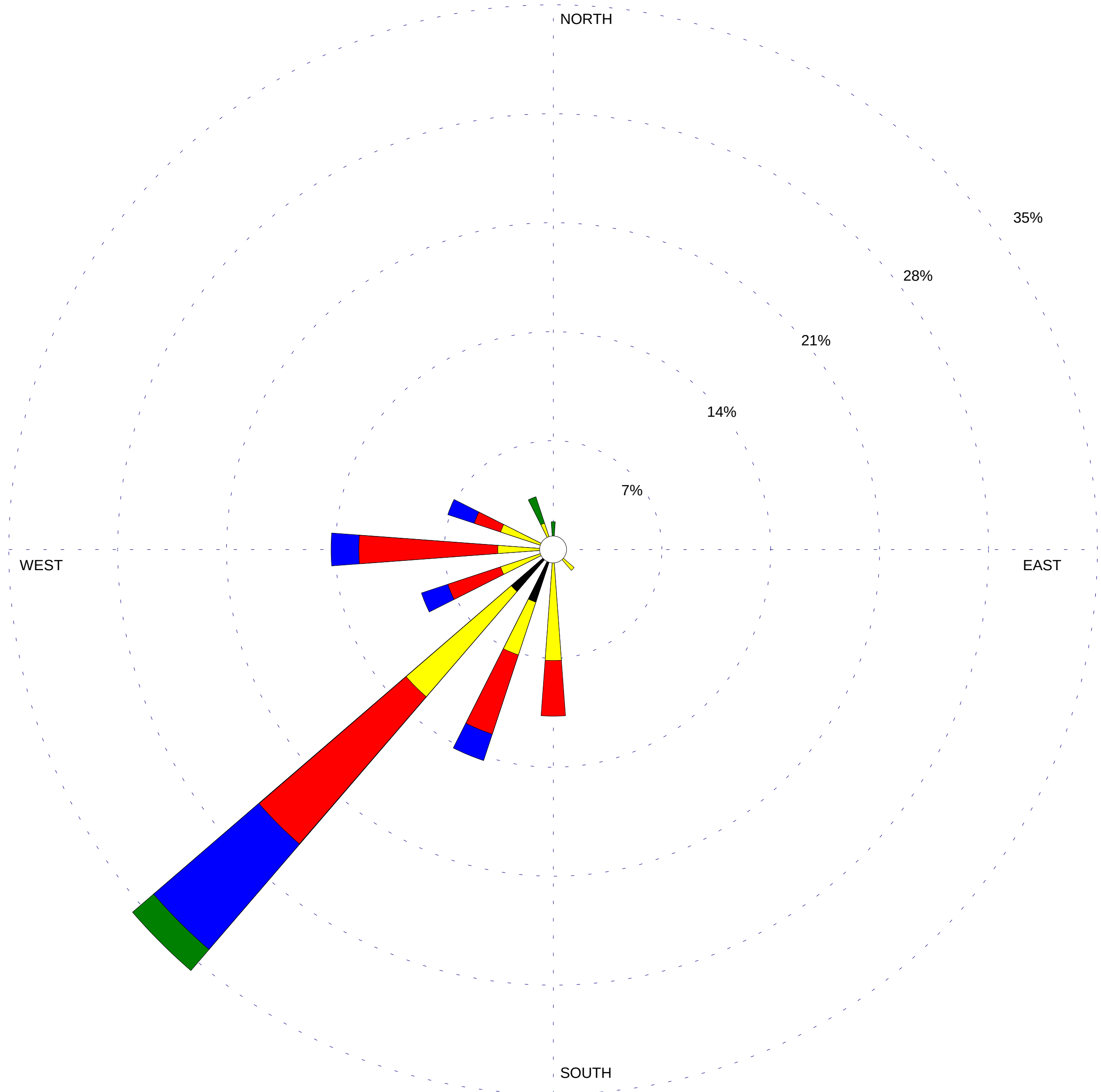


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **5.25 m/s**	CALM WINDS **0.00%**	
	Direction (blowing from)	**1996** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #Oakland 500mb June-September 1997

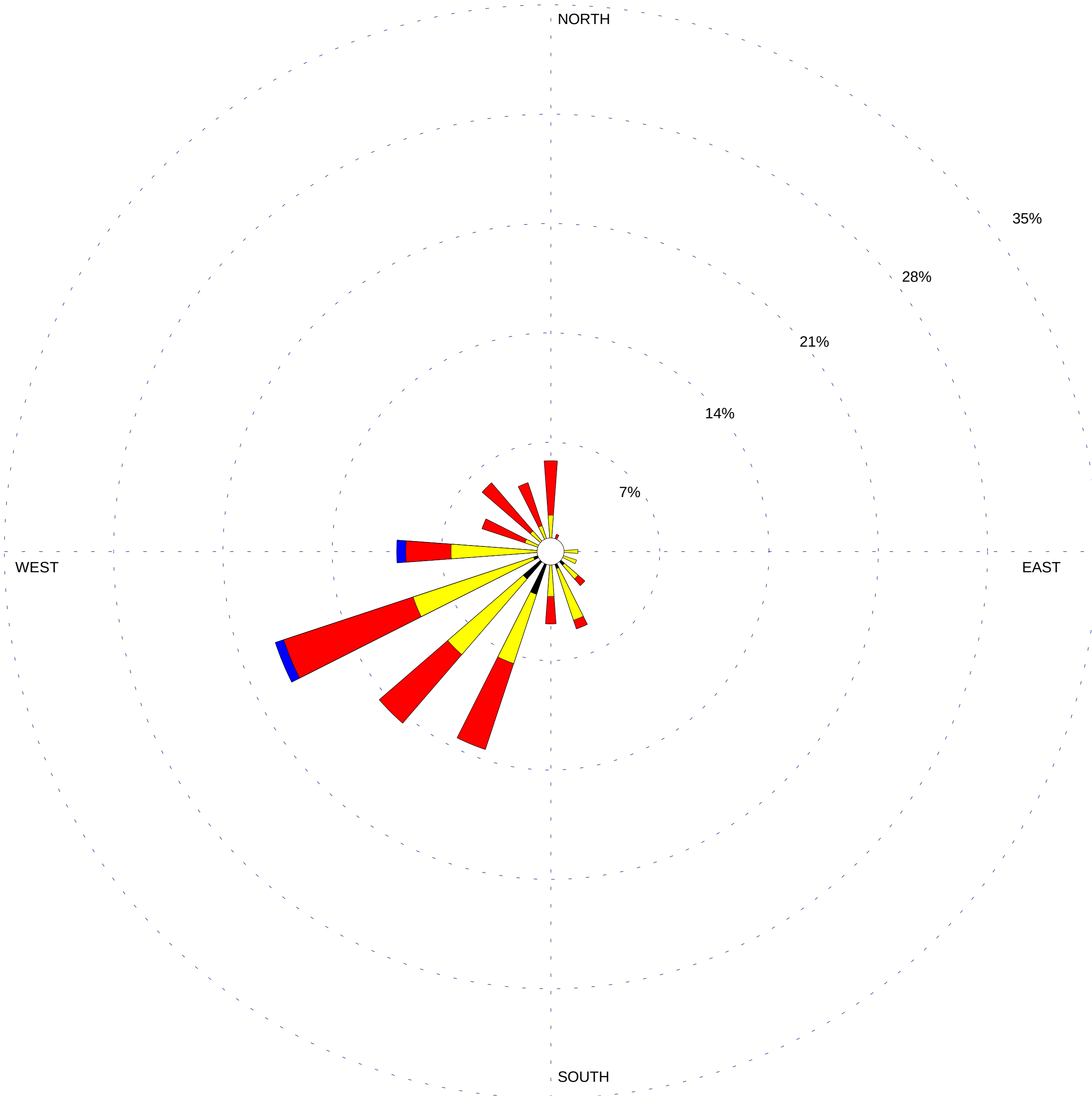


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **6.76 m/s**	CALM WINDS **1.79%**	
	Direction (blowing from)	**1997** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #OAK 500mb June-September 1998

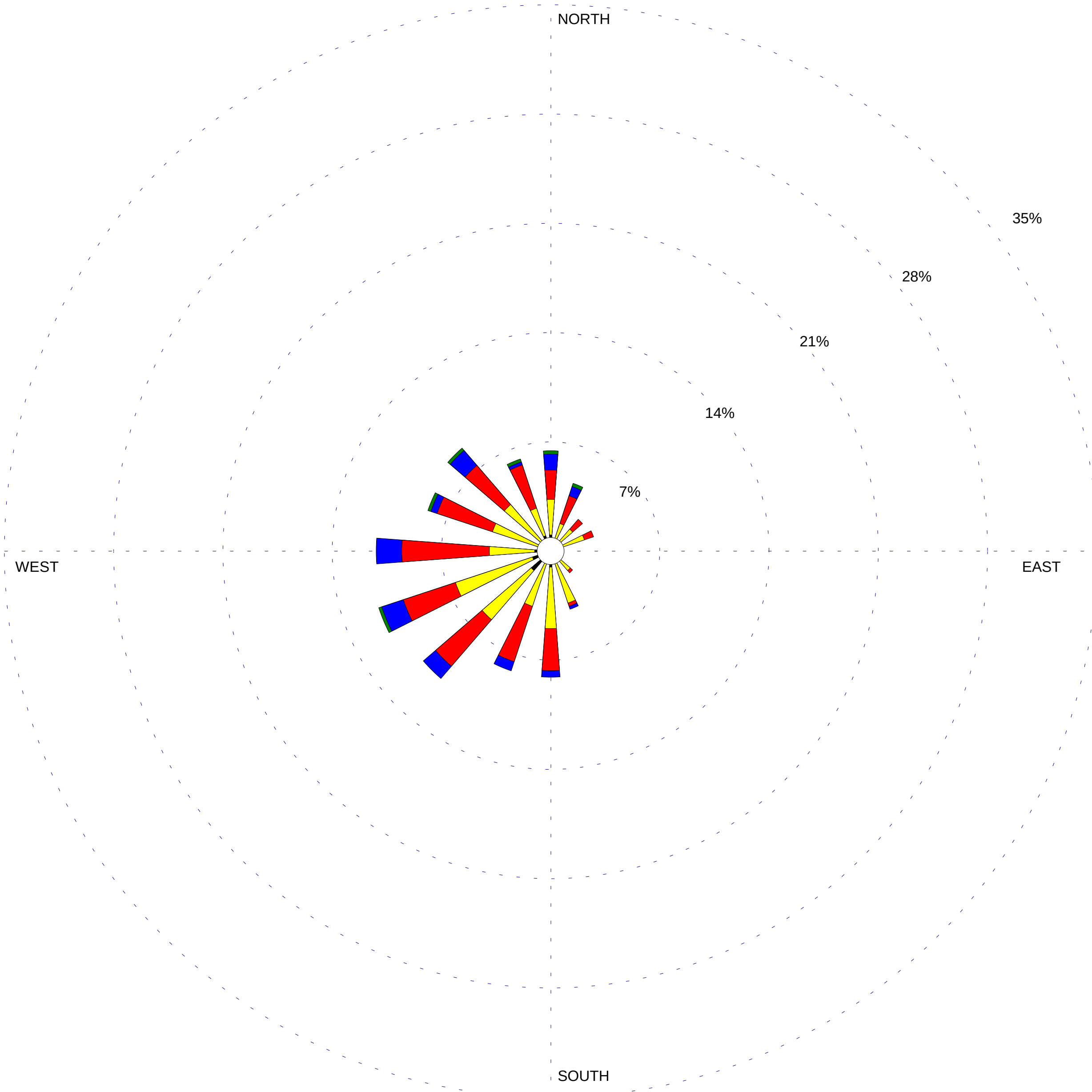


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
15.00 - 20.00			
10.00 - 15.00	AVG. WIND SPEED **4.84 m/s**	CALM WINDS **4.07%**	
5.00 - 10.00			
2.50 - 5.00	**Direction (blowing from)**	**1998** **Jun 1 - Sep 30** **Midnight - 11 PM**	
1.00 - 2.50			

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #OAK 500mb June-September 1999

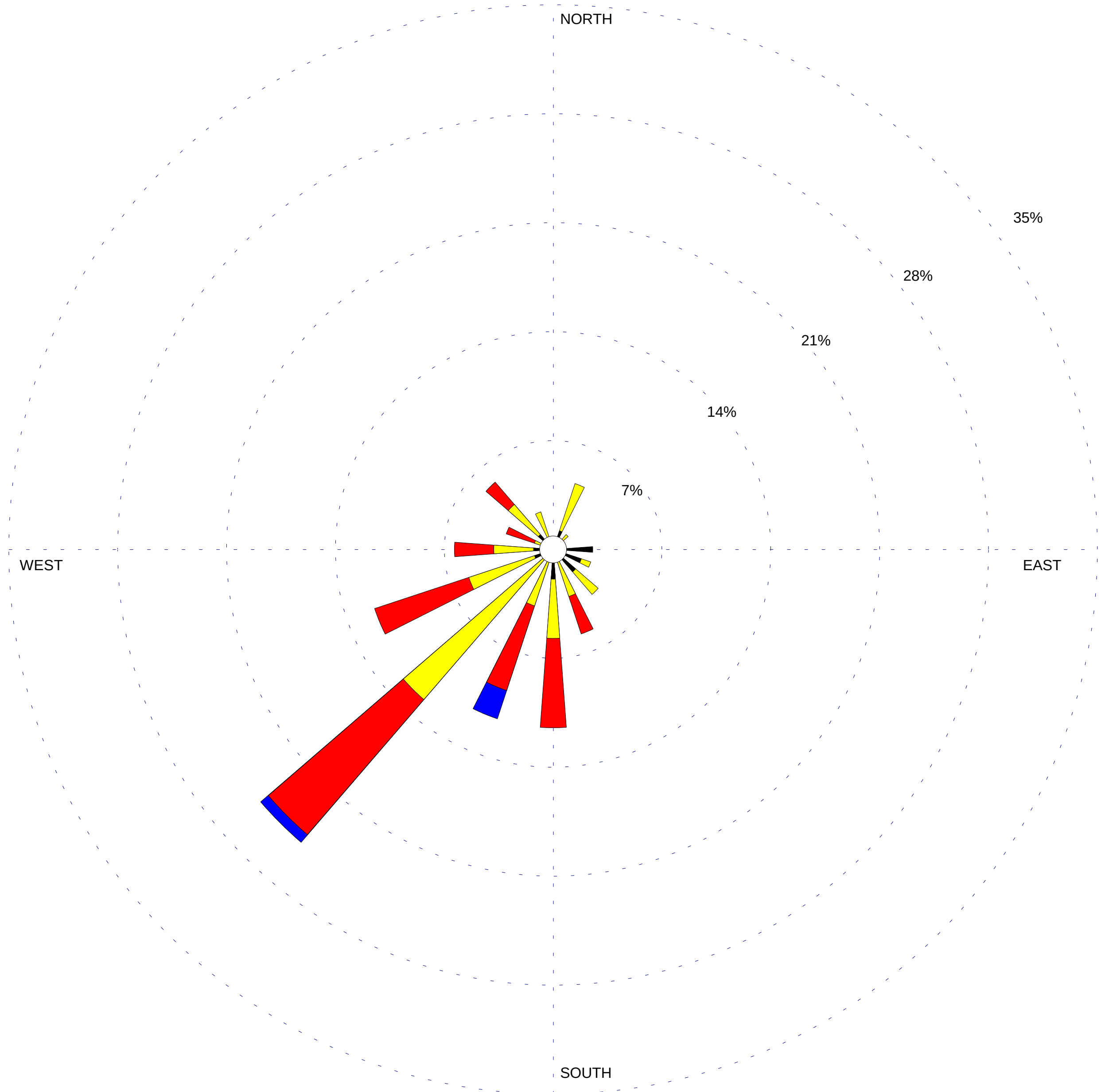


Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00 15.00 - 20.00 10.00 - 15.00 5.00 - 10.00 2.50 - 5.00 1.00 - 2.50	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
	AVG. WIND SPEED **5.61 m/s**	CALM WINDS **3.11%**	
	Direction (blowing from)	**1999** **Jun 1 - Sep 30** **Midnight - 11 PM**	

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

CCOS Analysis 01-2

Station #OAK 500mb June-September 2000



Wind Speed (m/s)		DATE **10/25/01**	T&B Systems **TB Systems**
> 20.00	DISPLAY **Wind Speed**	Units: **m/s**	COMMENTS
15.00 - 20.00			
10.00 - 15.00	AVG. WIND SPEED **4.97 m/s**	CALM WINDS **1.91%**	
5.00 - 10.00			
2.50 - 5.00	**Direction** **(blowing from)**	**2000** **Jun 1 - Sep 30** **Midnight - 11 PM**	
1.00 - 2.50			

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com